TRANSACTIONS OF
THE
OPTICAL SOCIETY

VOL. XXVI. 1924-25 NO. 2.

A NEW TYPE OF NEPHELOMETER

BY R. KINGSLAKE, A.R.C.S., B.Sc.

(Research Student in the Optical Engineering Department,
Imperial College of Science and Technology.)

MS. received, 13th November, 1924. Read and discussed, 13th November, 1924.

ABSTRACT. A new type of nephelometer is described, which provides an accurate optical method of measuring a minute amount of precipitate by means of the turbidity it produces in solution. Light is passed into the end of a tube containing the solution, and the intensity of the scattered light is measured by a special form of wedge photometer. A description is given of the means by which stray light can be kept from the eye during observations, and an actual example is included to illustrate the use of the instrument.

INTRODUCTION

IN the course of chemical, biological, and medical work it is frequently necessary to measure the opalescence of a solution, by which is meant the scattering of light by extremely small particles held in suspension in the liquid. Rayleigh* showed that for one particle the ratio of the intensity of the scattered light to that of the incident light is proportional to $\frac{T^2}{\lambda^4}$, where T is the volume of the particle and λ is the wave-length; and hence, for a given size of particle, the intensity decreases as the wave-length increases. This provides an explanation for the bluish colour of most opalescent solutions, such as, for example, ordinary tap-water to which have been added a few drops of silver nitrate solution.

Determinations of opalescence in the laboratory often form a very convenient and sensitive method of quantitative analysis, especially in cases where a direct chemical method is precluded by the extremely small amount of substance to be measured. Tyndall† first made determinations of the scattering of light by minute

* Wood, *Physical Optics*, 2nd edn., p. 626.
† Thorpe, *Dictionary of Applied Chemistry*, new edn. (1921), p. 520.

particles in gases, and Richards* in 1894 devised an instrument to measure opalescence in liquids, which he called a Nephelometer (from the Greek νεφέλη, a cloud). This instrument consisted essentially of two glass tubes containing opalescent liquids, which were illuminated from the side, and the relative brightness of the scattered light was observed at the upper ends of the tubes. Kober in 1915 considerably improved on Richards' apparatus, although retaining the same principle, and his nephelometer† is the one most largely used at the present time.

Some years ago Prof. A. F. C. Pollard suggested and used an inversion of Richards' principle, that is, a beam of light was projected into the end of a glass tube containing the opalescent liquid, and the scattering was observed through the walls of the tube. A rough apparatus showed this arrangement to be highly sensitive, and in the present instrument this principle is applied in a convenient laboratory form.

Description of the Instrument

The solution to be observed is placed in a vertical glass tube similar to a polarimeter tube, about 80 mm. long and 12 mm. in diameter; and, in order to facilitate cleaning, the end-plate at the bottom is held in position by a screwed cell. A parallel beam of light is passed up into the lower end of the tube, and evidently the intensity of the scattered light will be brightest at the bottom and diminish gradually up the solution. It therefore becomes necessary to measure this brightness at a definite distance up the tube by some photometric arrangement. The photometer employed takes the form of another tube of opalescent liquid, about 25 cm. long, which is illuminated in precisely the same manner as the short tube, and which can be racked up and down until the brightness of the light scattered from the two tubes

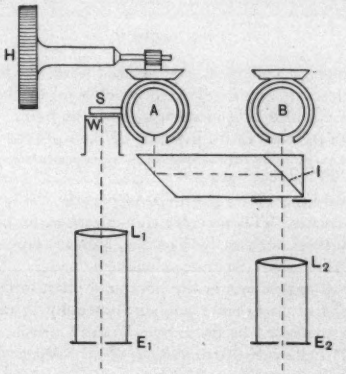


Fig. 1

* *Amer. Chem. Journ.* 31 (1904) 235.

† *Journ. Ind. Eng. Chem.* 7 (1915) 843.

is the same. A scale fitted to the sliding long tube will then give a measure of the opalescence of the liquid in the fixed short tube.

In order to bring the two matching fields into optical contact, a Nutting prism, having the interface *I* (Fig. 1) silvered in two horizontal bars, is found convenient. The field is then a tripartite one, with the upper and lower bands illuminated by tube *A* and the central band by tube *B*. Many photometers have only one division line to the field, but the use of two divisions prevents the possibility of error being introduced by retinal fatigue, because both dividing lines must disappear at once when making a setting. Since the central band on the prism is only $\frac{1}{16}$ inch in width, a simple magnifier of 1 inch focal length is inserted at L_2.

The tubes *A* and *B* are carried by metal sheaths mounted in vertical dovetail slides, and cut away in front to permit the free passage of scattered light to the photometer. The sheath carrying the short tube *B* containing the test solution can be clamped at any desired height, and the other sheath with the long tube *A* is moved up and down by a rack and pinion motion indicated in the diagrams. A German-silver millimetre scale *S* is attached to the side of this sheath.

Just in front of the scale is fixed a horizontal cross-wire *W* which is observed through the magnifying lens L_1, and a telecentric stop at E_1 eliminates any possible error due to the wire *W* not being in actual contact with the scale. A telecentric stop is also placed at E_2 to ensure that only parallel light from the tubes *A* and *B* ever reaches the observer's eye. A colour-filter is inserted at E_2 to counteract any differences in colour of the light scattered from the two tubes.

In all critical photometric work it is absolutely essential to have and to keep the eye dark-adapted; hence the instrument must be used in a dark room, and all stray light must be carefully removed. For this purpose the two sliding sheaths are enclosed by stout brass tubes. These carry at their upper ends the prism-box, and are mounted on the aluminium box containing mirrors (Fig. 2) and condensers

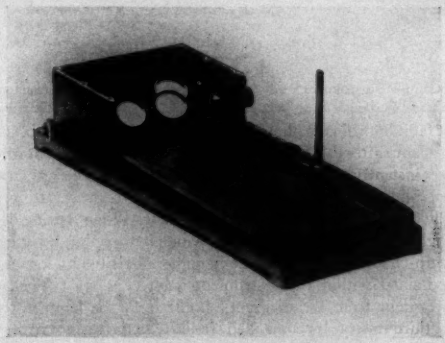


Fig. 2. Base of instrument showing mirrors.

by which parallel beams of light are sent up into the glass tubes. These mirrors are mounted on trunnions and can be completely adjusted by outside milled heads working in horizontal slots. Each mirror can thus be tilted by rotating the head, and turned about a vertical axis by moving the axle along the slot. These slots are rendered light-tight by disks of thin leather inside. A well-ventilated aluminium box (Fig. 3) round the lamp serves to keep in stray light from that source and, when all is in adjustment, a black cloth-covered screen may be placed round the sheaths to prevent light from escaping there. Fig. 4 shows the instrument with the lamp-box removed.

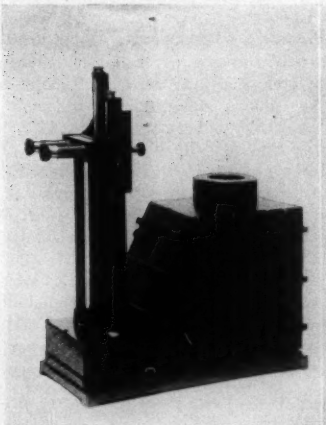


Fig. 3. Complete instrument ready for use.

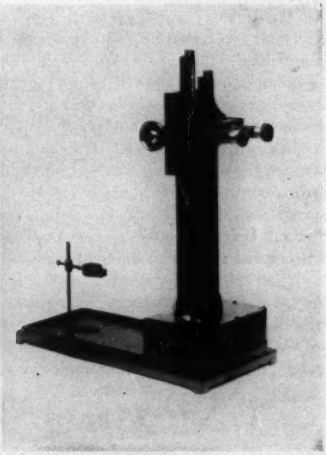


Fig. 4. View of instrument with lamp-box removed.

A frequent fault in ordinary photometric apparatus is that the observer generally has to turn on a lamp after each setting to read the scale and write down the reading. This of course instantly destroys the dark-adaptation of the eye, necessitating a delay of several minutes in the dark before attempting the next setting. This defect has been largely overcome in the present instrument. When writing down readings a little stray light can be let out on to the paper by opening a sliding shutter in front of the lamp-chamber, and the scale is rendered visible by means of a vertical illuminator contained within the instrument itself (Fig. 5). The action of the illuminator is evident from the diagram. Light from the lamp is reflected up a brass tube by a third mirror M_3 controlled similarly to the main mirrors M_1 and M_2. The beam is thence reflected on to the scale and cross-wire by a piece of plane

glass set at 45° to the axis of the eyepiece. This illuminator gives a very bright patch of light on the scale, and makes it perfectly easy to obtain accurate readings; but if it should be so bright as to upset the dark-adaptation of the eye, a slight tilt of the mirror M_3 will remedy this. A thin metal plate is fitted between the vertical illuminator and the Nutting prism to prevent any of the illuminator light from reaching the main eyepiece. A sliding shutter is provided below the illuminator tube so that the left eye need not be kept closed whilst making settings with the right.

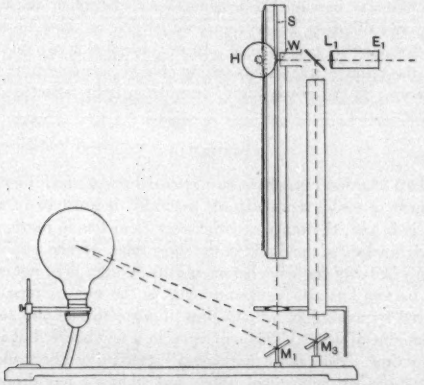


Fig. 5

Illuminants

A 100 c.p. direct-current "Pointolite" lamp is the ideal illuminant for this apparatus, but where expense must be kept down, a 100 watt projection-type gas-filled filament lamp could be substituted. It is essential that the light source should be as small and as concentrated as possible.

Use of Apparatus

A suitable lamp is mounted in its clip centrally with regard to the two main mirrors, and the lamp-house is placed in position, care being taken to render the joints light-tight. The sheaths are then set at the same height, the glass tubes being removed, and the mirrors are adjusted to give equal circular patches of light on a piece of thin white paper laid over the tops of the sheaths. This ensures that the light will pass axially up the glass tubes when they are replaced. The illuminator mirror should also be adjusted to give the correct amount of light on the scale. The solution to be measured is placed in the short tube, and a standard (see below) in the long tube. The short sheath should be clamped at such a height

that observations may be made near the middle of the liquid column, and a rough scale is engraved behind the dovetail slide of this sheath so that it may be re-set at the same height if required. The standard is then racked up and down until a photometric balance is obtained, which will be apparent by complete disappearance of both division lines of the field. If comparatively strong solutions are used, or if the setting is made near the lower end of the tube, the brightness may even vary over the height of the photometric field, in which case settings are made at the position of equal contrast over the two divisions, that is, the brightness of the central band must be mid-way between the brightnesses of the upper and lower bands.

In this way two solutions can be compared by placing them successively in the short tube, and making settings for each. In any observation several settings should be made and the average taken. No setting should be made near the surface of the solution, owing to the possibility of error from light reflected downwards by the meniscus.

Standards

The standard solution must have two essential properties. Firstly, it must be either permanent or easily repeated; and secondly, it must be of such a density that, when it is in use, the range of brightness from top to bottom shall include all possible brightnesses of the liquid in the short tube. Hence a universal standard must necessarily be fairly dense nephelometrically in order to be not only sufficiently bright at the bottom but also sufficiently faint at the top. A repeatable standard can be prepared by mixing known amounts of silver nitrate and sodium chloride in a known amount of water. This will settle in a few hours, but it can be made up again at any time. A suitable "permanent" standard can be made by dissolving some good-quality soap in distilled water, and adding a few drops of phenol to prevent decay. This solution is boiled and filtered twice, after which it should be left for about a month to settle, and then filtered again. A solution made in this way is practically permanent, and can be prepared of such a strength as to cover all degrees of opalescence commonly encountered. A silica gel made by adding acetic acid to a solution of sodium silicate can also be prepared of suitable density, and has the advantages of being unspillable and, if kept stoppered, practically permanent. Probably an agar or gelatine gel could be made of the right density, and this would be practically permanent too, if very well sealed from the air.

Interpolation

The process involved in making a determination with the instrument is best explained by an actual example, and the case chosen is that of the estimation of small amounts of silver or chloride in solution.

Solutions of silver nitrate were first made up, containing $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, 1, $1\frac{1}{2}$, 2, and 3 parts by weight of silver per 100,000 of water. A slight excess of potassium chloride was dissolved in each, and the whole was left to stand for an hour for precipitation to occur. Then the solutions were successively placed in the short tube, the sheath

being of course maintained at a fixed height throughout, and settings were made for each solution. A few typical sets are given, and these indicate the possibility of repeating settings with this instrument.

	cm.	
5·33	5·52	10·82
5·28	5·50	10·85
5·26	5·49	10·79
5·30		
5·25	5·00	
5·29	4·98	
5·28	4·89	

A curve (Fig. 6) was now plotted, relating average scale readings and corresponding strength of solution, from which the strength of any unknown solution of silver or of chloride can be read off by making a similar setting for the unknown solution. Corresponding scales for the abscissae of the graph are calculated for chloride and for silver, so that the method may be applied to a determination of either radicle.

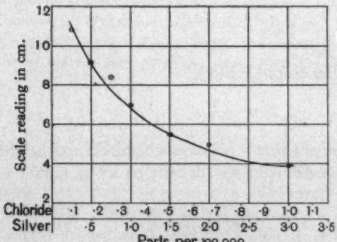


Fig. 6

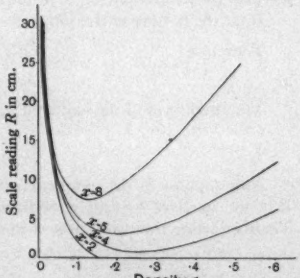


Fig. 7

In an actual experiment, 30 c.cm. of the laboratory tap-water were mixed with 5 c.cm. of silver nitrate solution, and the mixture left to stand for an hour. Settings were then made on this, giving an average reading of 7·60 cm., which on reference to the graph corresponds to 2·5 parts of chloride in one million of the solution. Since the tap-water was diluted by $\frac{35}{30}$ in making up the solution, it is evident that the original tap-water contained $\frac{7}{6} \times 2{\cdot}5 = 2{\cdot}92$ parts of chloride per million.

Form of the Calibration Curve

An exact mathematical treatment of this problem is impossible owing to the unknown amounts of stray light, internal reflections, etc. which occur in the apparatus. However, a rough indication may be obtained as to the shape of the curve in the following manner. We will commence by making several assumptions,

none of which can be regarded as holding in practice, but all of which are so nearly true that they will not seriously affect the *shape* of the curve obtained:

(1) The two beams of light are perfectly collimated.

(2) Any thin transverse layer of the liquid always scatters a fixed fraction of the light passing through it, and all this scattered light emerges through the walls of the tube.

(3) There is no stray light, and no light is internally reflected within the tube.

(4) The particles in the liquid do not directly absorb any light.

Consider one tube. Suppose ϕ is the fraction of light scattered per cm. along the tube, and let i be the amount of light inside the tube at a height x cm. Consider a narrow transverse layer at height x cm. and thickness dx cm.; then the amount of light scattered by this layer is $\phi i\,dx$. Thus

$$di = -\phi i\,dx \quad \text{or} \quad \frac{di}{i} = -\phi\,dx,$$

whence, by integration, $\log_e i = A - \phi x$.

If, at the bottom of the tube, $x = 0$ and $i = i_0$, we have $A = \log_e i_0$.

Therefore $$\log_e i = \log_e i_0 - \phi x$$

or $$i = i_0 e^{-\phi x} \qquad \text{.....(1).}$$

The brightness of the scattered light at height x will be

$$\beta = \frac{di}{dx} = -\phi i_0 e^{-\phi x} \qquad \text{.....(2).}$$

Now suppose in the complete instrument that a balance is obtained at a height R of the standard (density ψ) with the above solution (density ϕ) set at height x. Then, equating the two values of β, we have

$$\beta = -\phi i_0 e^{-\phi x} = -\psi i_0 e^{-\psi R} \quad \text{or} \quad \frac{\phi}{\psi} = e^{\phi x - \psi R}.$$

Therefore $$\phi x - \psi R = \log_e \frac{\phi}{\psi} \qquad \text{.....(3).}$$

From this equation the relation between R and ϕ is plotted (Fig. 7), with the arbitrary value of $\psi = 0{\cdot}1$, for $x = 2$, 4, 5, and 8 cm. respectively. It is evident from the curves that an ambiguity might easily arise as to the actual strength of a solution if the calibration curve were allowed to include the region of the minimum point. Hence, when measuring dense solutions, it is essential to keep the value of x as small as convenient.

My best thanks are due to Prof. Pollard for suggesting the principle, and for the great interest he has taken in the design and construction of the instrument; to Mr G. E. Gardam for help with the chemical part of the work; and to the makers* for their valuable assistance in the practical working out of the mechanical design.

* The instrument is made by Messrs Wray, Ltd., Optical Works, Bromley Hill, Kent.

REFERENCES TO NEPHELOMETRIC METHODS

Albumen, proteins, casein, globulin, etc.: Kober, *Journ. Amer. Chem. Soc.* 35 (1913) 1585; Marshall and Banks, *Proc. Amer. Phil. Soc.* 54 (1915) 176; St. Rusznyak, *Biochem. Z.* 133 (1922) 365.
Ammonia, calcium, acetone, fats, and phosphorus: Kober, *Journ. Ind. Eng. Chem.* 10 (1918) 558.
Chloride and silver: Richards and Wells, *Amer. Chem. Journ.* 31 (1904) 235; *Journ. Amer. Chem. Soc.* 27 (1905) 459; Guye, *Journ. Chim. Phys.* 10 (1912) 145.
Chlorine, in poison gas: Lamb, Carleton, and Meldrum, *Journ. Amer. Chem. Soc.* 42 (1920) 251.
Cholesterol and higher fatty acids: Czonka, *Journ. Biol. Chem.* 34 (1918) 577.
Colloids: Sheppard and Elliott, *Journ. Amer. Chem. Soc.* 43 (1921) 531.
Coloured hydrosols: Bechhold and Hebler, *Kolloid. Z.* 31 (1922) 7.
Fats in milk: Bloor, *Journ. Amer. Chem. Soc.* 36 (1914) 1300.
Nucleases: Kober and Graves, *Journ. Amer. Chem. Soc.* 36 (1914) 1304.
Nucleases and proteases: Kober, *Journ. Biol. Chem.* 13 (1913) 485.
Phosphates: Kleinmann, *Biochem. Z.* 99 (1919) 115; Feigl, *ibid.* 102 (1920) 131.
Sulphates: Dienert, *Compt. Rend.* 158 (1914) 1117.
Use in Biochemistry: Osborn, *Physiol. Abstr.* 3 (1918) 221.

DISCUSSION

Dr J. S. Anderson: If it is necessary to have accurate standards for the instrument, I do not think that any colloidal preparations, such as the soap hydrosol or silicic acid gel exhibited, will be satisfactory. One characteristic of most colloidal preparations is continuous, though possibly slow, change.

Mr F. F. S. Bryson: It has occurred to me that opal glass would form a suitable standard, provided that the particles are uniform and fine enough.

Mr P. F. Everitt: A cored carbon, in which the soft core has been replaced by direct powdered salt, could be employed to produce a sodium arc which, when used in connexion with suitable screens, would give approximately monochromatic light. This could be used to investigate the effect of the change of effective wave-length with length of the tube used as a standard.

Mr Kingslake: The problem of obtaining an accurate, truly permanent standard is difficult, and those suggested in the paper were the only ones thought of in the time available. Mr Bryson's suggestion to use an opalescent glass rod is a good one, and such a rod would be an ideal standard if it could be obtained of suitable and of uniform density. It is, however, essential that the particles causing the

turbidity should be sufficiently small to *scatter* the light without merely reflecting it diffusely.

In reply to Mr Everitt, a bright monochromatic illuminant is distinctly desirable, but the arc light is of such a fluctuating and variable nature as to be entirely unsuitable for any photometric work. Moreover, a pure monochromatic light is by no means necessary, and it has been found by experiment that a yellow or an orange filter in the eyepiece is quite sufficient to match the colours of the light from the two tubes in all ordinary cases. A filter certainly absorbs an appreciable percentage of the light, but the convenience and simplicity of the present arrangement completely outweigh this disadvantage.

SOME NOTES ON NEPHELOMETRY AND A SUGGESTED SENSITIVE TEST FOR THE STABILITY OF EXPLOSIVES

By Professor A. F. C. POLLARD, A.R.C.S., A.M.I.E.E.

(Optical Engineering Department, Imperial College of Science and Technology.)

MS. received, 12th February, 1925. Read (in abstract), 13th November, 1924.

ABSTRACT. The importance of nephelometry to industry and the chemist is indicated, and the unsatisfactory state of the theory of the molecular as well as the colloidal scattering of light is briefly discussed. An example of the high sensitivity of nephelometric methods is given in a description of some preliminary work upon a suggested sensitive test for the stability of nitro-explosives and the simple instrument designed for the purpose.

The Importance of Nephelometry

Nephelometric methods and apparatus may conveniently be divided into two classes, those by means of which the amount of matter present in smokes or solutions in the form of suspended particles may be detected and measured and those by means of which the molecular scattering of light by gases, vapours, pure liquids and transparent solids, such as glass, crystals, etc., may be studied. The instrumental requirements for the study of these two classes of phenomena differ. Instruments for measuring the turbidity of solutions obvious to the unaided eye or the amount of suspended matter in visible smokes or fumes are not difficult to design, since the light scattered from such gross states of matter is a comparatively large fraction of the incident light.

On the other hand, molecularly scattered light is of such feeble intensity, being only of the order of 10^{-7} of that of the primary beam in pure liquids, that it is difficult to observe, is readily reduced by reflections from the transparent surfaces of the containing vessel or those of the observing optical system, and is extremely difficult to isolate from stray light scattered from parts of the apparatus itself. In the present crude state of nephelometry it cannot be said that any single instrument has yet been designed which will measure with any degree of accuracy molecularly scattered light as well as the light scattered from colloids. Instruments, however, which are capable of measuring the light scattered from matter in the colloidal state approaching the molecular state with the usual photometric accuracy are of extreme industrial importance and much needed. It is certain that such an instrument would be a powerful tool of research to the chemist.

Theory

A great deal of theoretical and experimental work on molecular scattering has been done since the late Lord Rayleigh* published his classical paper on the blue colour of the sky, and has been ably summarized and discussed by Professor C. V. Raman in his book *Molecular Diffraction of Light*. Rayleigh's formula for the intensity of the scattered light is generally taken as the theoretical basis of the nephelometry of colloids and feeble precipitates, though he has expressly stated that his results apply only to gases. His formula is based upon the supposition that the distribution of the phases of the scattered waves arising from the individual molecules is a random distribution. This requires the molecules themselves to have a random distribution, which implies that the probability that two or more given molecules are found together within a specified space is the product of the probabilities of each of them separately being found within the space. That is to say, the molecules must be so spaced that their spheres of mutual action are a small fraction of the total volume occupied by them. This is precisely the condition necessary to satisfy Boyle's law, so that Rayleigh's results do not even apply to gases near their critical points, much less to colloids.

In pure liquids the spacing of the molecules is far less than in gases and consequently there is a partial correlation of the phases of the waves emitted by the molecules, so that interference of the scattered light takes place and the intensity is not so great as otherwise would be expected.

This difficult and complicated problem has been attacked by Einstein† and Smoluchowski‡ with the aid of the statistical thermodynamical method, and the results have been especially applied to the remarkable opalescence exhibited by liquids near the critical state.

The theory, which depends upon the assumed truth of Maxwell's electromagnetic equations and continuity of energy exchanges, asserts that the intensity of light scattered by a cubic centimetre of liquid at right angles to the primary beam of wave-length λ is

$$\frac{\pi^2}{18} \cdot \frac{R \cdot T \cdot \beta}{N_1} \cdot \frac{(\mu^2 - 1)^2 (\mu^2 + 2)^2}{\lambda^4},$$

where R is the gas constant, N_1 Avogadro's constant, β the compressibility, T the absolute temperature, and μ the refractive index. The scattering therefore depends upon the temperature and the variation of compressibility and refractive index with change of temperature.

In the case of gases $\beta = \frac{1}{p}$ and, as μ only differs slightly from unity, $\mu^2 + 2 = 3$ nearly and the formula then reduces to Rayleigh's result. The light scattered by liquids, however, is imperfectly polarized and it is thus necessary to apply a correction due to Cabannes who took account of the anisotropy of the molecule§.

* Lord Rayleigh, *Phil. Mag.* 41 (1871) 107, 279; *Scientific Papers*, vol. 1, p. 87.
† Einstein, *Ann. der Phys.* 33 (1910) 1275.
‡ Smoluchowski, *Ann. der Phys.* 25 (1908) 205.
§ See C. V. Raman, *Molecular Diffraction of Light*, p. 50.

Though the theory, when corrected for the anisotropy of the molecule in this way, describes fairly accurately the scattering from non-fluorescent liquids and gases, it breaks down in the case of gases under high pressure. It will thus be seen that the theory of the molecular scattering of light is in an unsatisfactory state.

When the particles of a suspended precipitate are so large that the incident light is reflected, then no doubt the scattering depends upon the size and number of particles per unit volume, and the total intensity is great in comparison with the feeble molecular scattering, but as the particles become colloidal and approach molecular dimensions the problem presents further difficulties. This supposition of proportionality of size and number of particles to scattering has been confirmed by many investigators for white turbidities, but is not true for coloured hydrosols* except when monochromatic illumination is used.

An Example of the Application of Nephelometry to the Study of the Stability of Nitro-explosives

As stated above, an instrument capable of measuring molecular or colloidal scattering in a convenient and accurate manner would be a powerful tool of research as well as of industrial utility, and no doubt such an instrument should be designed to compare photometrically and macroscopically the scattering from two small and intense Tyndall cones produced by the method of Siedentopf and Zsigmondy now universally used for ultra-microscopic observations. Nevertheless it may be of interest to show how sensitive nephelometric methods may be, even with imperfectly designed apparatus, by describing briefly the preliminary work upon a nephelometric test for the decomposition of nitro-explosives.

When such explosives decompose, it would appear that extremely minute quantities of nitrogen peroxide are liberated and all stability tests consist of methods for measuring the rate of evolution of the gas.

In the well-known Abel's heat-test, the explosive is placed in a test-tube and heated to 180° F. in a water bath. A test paper containing starch and potassium iodide is suspended by a platinum wire in the tube, from a cork. The test paper is moistened with glycerine and water to wet it half-way down. The time taken for the concentration of the peroxide of nitrogen within the tube to rise to a sufficient value to cause a faint yellow line on the test paper at the junction of the wet and dry portions is measured. The test is apparently simple to carry out and is the oldest and most used of all the tests. But it gives no real gauge of the stability of the explosive or its liability to decompose; the absorption of gases by the paper and production of the yellow line are somewhat erratic phenomena depending upon unknown as well as known causes, and the test is affected by the presence of moisture and volatile impurities. Moreover the test requires the explosive to be heated to a comparatively high temperature, thus exposing it to abnormal conditions which do not conform to those of storage.

It occurred to me that if pure dry air was passed over the finely-divided explosive, in the case of propellants, and bubbled into a suspended colloid which was

* H. Bechhold and F. Hebler, *Koll. Z.* 31 (1922) 7.

soluble in the nitrogen acids and not electrically coagulable by the process of bubbling, the accumulated gas could be swept out and measured, provided that the changes in the colloid could be seen and measured. Further, it might even be possible to measure the rate of evolution of the gas by sweeping out measured quantities of gas in known intervals of time.

After some preliminary work upon various colloids, such as those of silver prepared by Bredig's method, extremely dispersed colloids of the oxide of silver were found to be very sensitive to the presence of the nitrogen acids and, if care was taken in the bubbling process, appeared neither to be coagulated by electrification nor to be very much affected by acetone. Richards' nephelometer was used in the early stages of the work, but was found to be misleading and useless for the measurement of such dispersed systems.

It therefore became necessary to design a more satisfactory instrument and moreover one in which the means for diminishing the light in the comparison field could be reproduced anywhere at any time at a low cost. The following arrangement was therefore devised.

Let A and B (Fig. 1) represent two tubes, one of which, A, is long and movable along its axis and the other, B, is short and fixed. The tubes are closed at their lower ends by flat end plates of glass. It is evident that if the two tubes are filled with a turbid liquid which does not deposit a precipitate upon the end plates, and parallel beams of light of equal intensity be directed along the axes of the tubes, light will be scattered in planes parallel to the trace XX, with diminishing intensity along the long tube from the bottom towards the top. Should the liquid in the tube B become from some cause less turbid than that in A, a position can be found for the tube A in which the scattered lights from the two in the plane are equal in intensity.

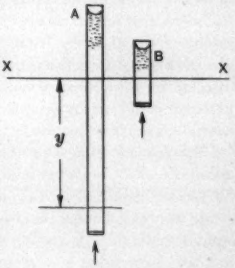


Fig. 1

Since the shorter waves of light during passage through turbid media are scattered at a greater rate than the longer, the incident and scattered light at higher levels in the tube A assumes a reddish tinge and it is then necessary to give the same colour value to the two fields in the plane XX by a filter which is suitable to the turbid media used. If, therefore, a standard solution is placed in the two tubes A and B and the colloid in B is partly dissolved, the tube A must be pushed downwards a distance y in order to obtain photometric balance.

Let I_A and I_B be the intensities of the light scattered from the tubes A and B respectively at the level XX. Then $I_A = I_B$.

But I_A must be some function of y which will hardly have the usual absorption form, since the scattering liquid has a reflecting boundary, but whatever form it has is of no importance to the performance of the instrument for moderately dispersed colloidal systems. Put, therefore, $I_A = f(y)$ and $I_B = \gamma m$, where m is the

quantity of matter per unit volume in the tube B and γ is some constant which depends upon the absorption rate of the liquid, the nature of the incident light, and the size of the particles. Hence $\gamma m = f(y)$ when $y = 0$, $m = M$, the standard amount of matter per unit volume. Hence $\gamma M = f(0)$, provided that the temperature has not changed or the mean size of the particles has not altered.

The amount of matter which has been removed from the tube B is then

$$M - m = \frac{1}{\gamma}\{f(0) - f(y)\},$$

so that, if in Fig. 2 ordinates represent values of y and abscissae values of $f(y)$, OC is proportional to the standard amount of matter in the two tubes when $y = 0$ and the curve CD represents the matter removed from the tube when CQ and PQ are its co-ordinates.

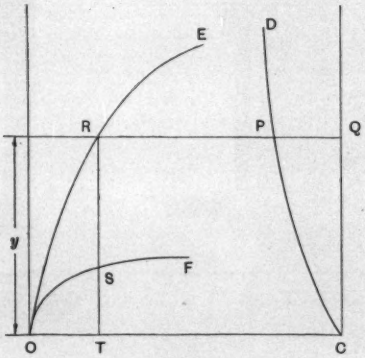


Fig. 2

This curve can be made the calibration curve of the instrument by placing known dilutions of the standard solution in the tube B and noting the position y of the tube A when a photometric match has been obtained.

Let it be assumed that the products of decomposition in the pure air which is bubbled into the solution in tube B at a constant rate are completely absorbed. Then OC may be taken as a time axis, and the curve OE plotted to represent the rate at which the long tube has to be pushed down to keep a photometric balance while the turbidity is disappearing from the tube B. Hence, if a second curve OF be plotted with ordinates $TS = QP$, the amount of matter removed in the time OT corresponding to the position $y = TR$ of the comparison tube, OF represents the rate at which the products of decomposition are diffusing into the air stream from the explosive.

A Simple Nephelometer

Several nephelometers based on the above notions were constructed with the main object of simplicity of construction and it may be of interest to mention one of these attempts after describing the instrument with which the decomposition of some nitro-explosives was determined at room temperature and pressure for the first time.

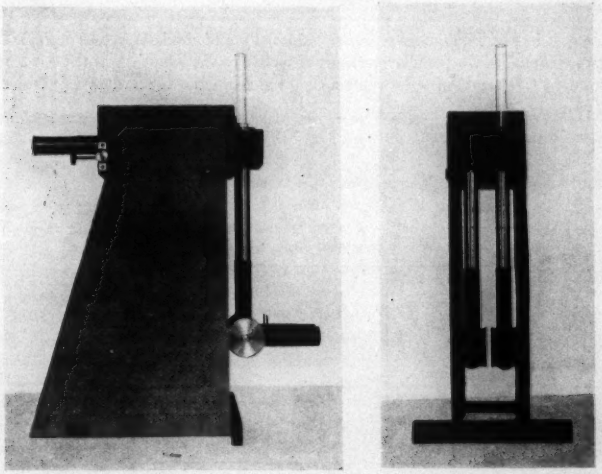


Fig. 3

Fig. 3 gives photographic side and front views of the instrument, which it will not be necessary to describe in detail since an improved form of the instrument* essentially similar has been described by Mr R. Kingslake.

The two glass tubes with end plates can be seen in the front view inserted into black velvet lined brass tubes, which carry at their lower ends each a right-angled prism housed in a cylindrical brass box.

The prisms can be turned about the horizontal and vertical axes in order to direct collimated light from a single source up the two tubes.

For this purpose two positive lenses are mounted in two short brass tubes which can be pushed into the horizontal tubes in front of the prisms and moved in or out for adjustment. Two diaphragms are seen immediately behind the lenses, but it was found better to place these actually on the bottom of the glass tubes.

* *Trans. Opt. Soc.* 26 (1924–25) 53.

The height of the tube *A* was measured with a millimetre rule placed against it.

Two rectangular openings are cut in the upper part of the velvet lined brass tubes to allow the scattered light from *A* and *B* (Fig. 4) to enter a bi-prism train *P*, *Q*.

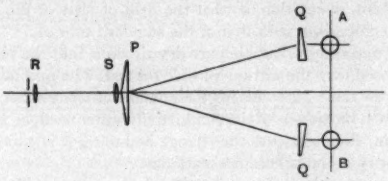


Fig. 4

The photometric field is divided by the vertical edge of the prism *P* and two similar positive lenses *R* and *S*, separated by a distance equal to their focal lengths, are placed one almost touching the edge of the prism and the other near the eye.

Parallel light scattered from *A* and *B* falls upon the lens *S* and floods the retina through the telecentric stop placed immediately in front of the lens *R*, which slightly magnifies the field and enables the edge of the prism to be seen distinctly.

Thus the aperture of the lens *S* is divided sharply into two fields, the left half appearing to be filled with light from the right tube and the right half with that from the left.

The achromatizing prisms *Q*, *Q* are used since the cylindrical boundary of the glass tubes interferes with the uniformity of the photometric field in the horizontal direction. The prism *P* is adjusted so that its vertical edge bisects the parallel bundle proceeding from each tube, which can be done by moving the prism sideways or backwards and forwards until a match along the edge is obtained when the two tubes contain the same solution and stand at the same level. Both these adjustments are made by the one milled head seen near the eyepiece (Fig. 3).

Though this instrument is not free from the defect of scattered stray light and is without means for controlling the temperature of the solutions, it has given good results.

Some Preliminary Experiments upon the Stability of Nitro-explosives

As stated above, it was found that suspended colloids of silver oxide were sensitive detectors of the nitrogen acids and one or two experiments will be described to indicate that possibly an extremely sensitive and accurate test has been found for the stability of explosives.

The colloids were prepared by adding dilute solutions of pure sodium hydrate to dilute pure silver nitrate, the oxide formed being almost invisible to the naked eye, but filling the nephelometer field with bluish light which in many cases was almost completely polarized. At the upper parts of the long tube the scattered light assumed a slightly reddish tinge but, by using a Wratten and Wainwright "E"

filter, this difficulty was overcome. It appeared necessary to have the silver nitrate considerably in excess of the sodium hydrate.

In some of the colloids prepared the absorption of 0·49 microgramme of nitrogen peroxide (or about 0·2 c.cm. at room temperature and pressure) completely dissolved the oxide in 5 c.cm. of solution, so that the field of view of the tube *B* appeared almost black in comparison with that of the standard tube *A*.

It was found necessary to bubble pure dry air alone into the solution in tube *B*, before it was passed over the nitro-explosive for test. The preliminary bubbling of the pure dry air in some cases lessens the amount of silver oxide, possibly by the liberation of carbon dioxide from the conductivity water used, or partly precipitates it by aggregation. But, whatever the change is due to, it is excessively small and after about 10 to 15 minutes becomes stationary.

Two experiments with cordite and two with gun-cotton will now be described.

A solution of 90 c.cm. $N/10$ pure silver nitrate and 10 c.cm. $N/10^3$ pure sodium hydrate was prepared. Pure dry air was passed through the solution in tube *B* for 65 minutes and no change could be observed. The air was then passed over finely-ground cordite of current manufacture size 16. The room temperature was 11° C. and the following readings were taken:

Time in minutes	0	20	50	60	75
y in mm. ...	0	35	125	140	158

A fresh quantity of the same solution was taken and the pure air passed over old low H.T. cordite at the room temperature of 11° C.

Time in minutes	0	10	20	30	45	55
y in mm. ...	0	25	60	100	150	200

To calibrate the comparator tube the solution was diluted and compared:

Proportional to amount of silver oxide in tube *B*	1·00	0·90	0·80	0·70	0·60
y in mm.	0	20	130	160	Too dark for comparison

These values are plotted in Fig. 5 and the rate curves drawn. It is evident that it would take a longer time to sweep out completely the explosives and that the rate at which the old low H.T. cordite was giving up its accumulated decomposition products was actually increasing at the end of the experiment.

Standard dried gun-cotton and partially stabilized gun-cotton H.T. 2 minutes were dried over sulphuric acid for six days. A solution was prepared by slowly adding 20 c.cm. of $N/10^3$ sodium hydrate to 80 c.cm. of $N/10$ silver nitrate. Three grammes of the standard gun-cotton were placed in the decomposition vessel at the room temperature of 14·2° C. and the following values observed:

Time in minutes	0	10	20	35	55	80	95
y in mm. ...	0	20	30	50	70	70	70

It will be noticed that change suddenly ceased to take place after 55 minutes.

Without disturbing the apparatus or the solution in *B* the same quantity of the

partially stabilized gun-cotton was substituted for the standard gun-cotton and immediately the comparator figures rose as follows:

Time in minutes	0	10	20	30	52
y in mm. ...	70	85	90	95	100

The comparator tube was calibrated.

Proportional to silver oxide in B	1·00	0·90	0·80	0·70
y in mm....	0	18	55	145

These results are plotted in Fig. 6. It is interesting to note the type of the rate curves, which are characteristic of the gradual elimination of the decomposition products from the explosive, and all the experiments which were performed suggested that these products accumulate in the explosive and reach equilibrium.

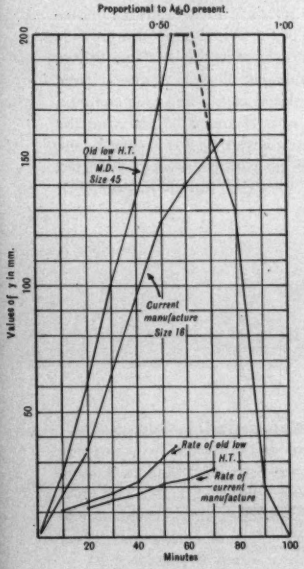


Fig. 5

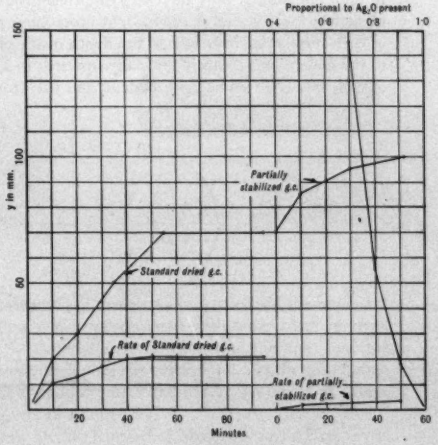


Fig. 6

Thus it would appear that the rate at which the silver oxide disappears and therefore probably the rate at which the peroxide of nitrogen comes over with the air stream, depending possibly upon the state of mechanical subdivision of the explosive and other factors, cannot be a measure of the evolution of the gas in the

mass of the explosive. It is evident that the test is not delicate enough to measure this time rate of gas evolution, for the curves may become flat if the air be passed over the explosive for a sufficiently long time.

But if two experiments be performed at a known interval of time, in which all traces of the products of decomposition are removed, then the true rate of decomposition may be defined as the amount of nitrogen peroxide accumulated in the interval per unit of time. The experiments show that this interval of time need not exceed 10 hours.

Enough has been said to indicate the sensitivity of nephelometric methods and at least their extreme importance to industry.

A Further Attempt to Simplify the Nephelometer for Industrial Use

In an attempt to simplify construction and to obtain a more uniform photometric field with cylindrical vessels, the properties of the ellipse suggest a possible instrument. In Fig. 7, B_1 and B_2 represent the internal reflecting surfaces of two shallow elliptical cylinders 4 mm. deep which intersect along a common focal diameter FF, with a right-angled reflecting cone placed at C, the focus common to both ellipses. If now the two cylindrical glass tubes A and B be placed at the other two foci A_1 and A_2, then light proceeding normally from a cylindrical zone of each tube equal in height to the depth of the elliptical surfaces will be reflected to the cone C and from it vertically upwards in a cylindrical bundle of light, half of which is made up of light from A_1 and half from A_2.

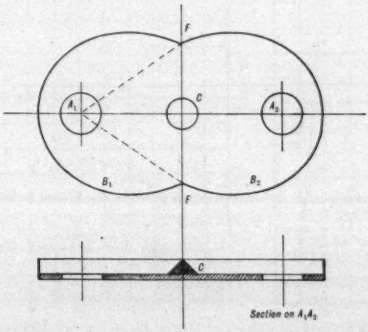


Fig. 7

Part of the instrument constructed on this plan is shown in the photographs (Fig. 8). The elliptical cylinders are represented by watch springs silvered on the inside and bent into ellipses. The right-angled cone is of polished speculum metal, which, when observed in the eyepiece with tubes in position filled with turbid

liquid and illuminated from below in the same way as in the previous nephelometer, appears as a uniform circle of luminosity sharply cut into two fields.

Since the light proceeding normally from the surface of the cylindrical tube between two close generators is ultimately reflected from between the corresponding generators of the surface of the cone, each tube appears in each field as a narrow sector-shaped dark shadow, cutting each field into two equal portions. But this did not interfere with the visual judgment of field equality.

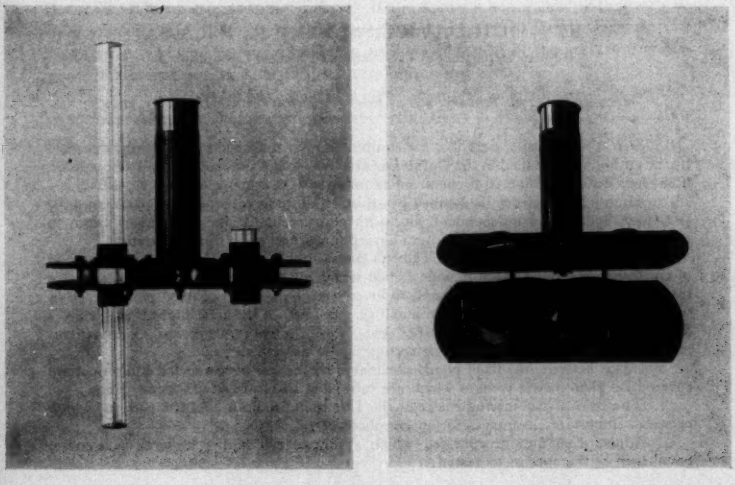


Fig. 8

On account of the imperfect reflection of the silvered surfaces and the imperfect absorption of the bounding planes which were coated with lamp black, a small amount of light from each tube is scattered and contributes to the light reflected from that half of the conical surface which does not correspond. As the elimination of this defect would require further complications and defeat the object of simple and cheap construction, the idea was abandoned.

In conclusion I desire to thank Mr W. Rintoul of Messrs Nobel's Explosives, Ltd., for kind permission to publish some results of the preliminary work on the test for the stability of nitro-explosives.

AN EQUIPMENT FOR VISUAL SPECTROPHOTOMETRY

By J. GUILD, A.R.C.Sc., F.Inst.P., F.R.A.S.
(Optics Department, The National Physical Laboratory.)

MS. received, 27th January, 1925. *Read (in abstract), 12th December*, 1924.

ABSTRACT. The paper describes the equipment for visual spectrophotometry designed by the author and installed in the Optics Department of the National Physical Laboratory. The chief features of the equipment are as follows:

1. High light efficiency is obtained by omitting all unnecessary optical parts from the test beam and having independent slit width adjustment for the comparison beam to compensate for the necessary minimum absorption of the measuring apparatus.

2. The basis of measurement is Talbot's law as applied to rotating sectors. A method of employing a series of sectors is described which enables the whole range of effective transmission from 100 to ·01 per cent. to be covered by a series of fixed points, each of which corresponds to a transmission about 90 per cent. of the next higher, with only a few sectors none of which is below 1 per cent. in its effective transmission. A convenient method of calibrating the small-angle sectors is also described.

The gaps between the fixed points obtainable by the use of the sector equipment are covered by photometric wedges which are calibrated in terms of the sector disks.

3. The field of the instrument is of the Lummer-Brodhun contrast pattern, which possesses important advantages for spectrophotometry.

4. Adjustments are incorporated which eliminate errors due to lack of accurate parallelism in the specimens tested.

Introductory

A considerable amount of spectrophotometric work has had to be carried out during the last few years in the Optics Department at the National Physical Laboratory in connexion with work on colour standardization.

The equipment at the commencement of this work consisted of a Koenig-Martens spectrophotometer by Schmidt and Haensch, the property of the Laboratory, and another instrument, of well-known type, kindly loaned by the Admiralty Research Laboratory. It was found that neither of these instruments was adequate for the purpose. The Koenig-Martens spectrophotometer is extremely wasteful of light owing to the nature of the optical system employed. It is

useless, on this account alone, for accurate measurements near either extremity of the spectrum where the luminosity is low.

The loss of sensitivity towards the ends of the spectrum, which is inevitable in any visual method of spectrophotometry, is of no importance if the purpose of the spectrophotometric measurements is to provide data for calculating the *luminosity* of the total light transmitted or reflected by a coloured body, because the regions of low luminosity contribute, *ipso facto*, very little to the total luminosity, and relatively large percentage errors in these regions have negligible effects on the total. The matter is quite different if the spectrophotometric data are to be used for computing the *colour* of the transmitted or reflected light. What may be termed the colouring value of radiation near the blue end of the spectrum is disproportionately large as compared with its luminosity value.

Thus, if blue light be mixed with its complementary yellow in such proportions as to make white, in which case we may regard them as of equal colouring value, since neither constituent is apparent in the mixture, the yellow light will be enormously brighter, if seen separately, than the blue.

In Fig. 1, which is taken from a paper by H. E. Ives*, is shown the relative luminosity of different wave-lengths in the spectrum of white light, and also the relative stimulation of the red, green, and blue sensations of the Young-Helmholtz theory, as deduced from Koenig's data. We see from this that the blue sensation

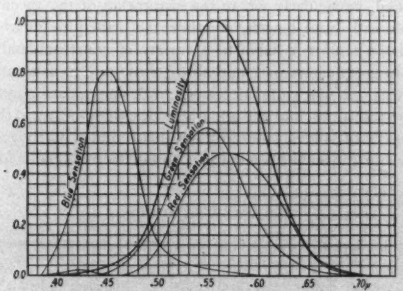


Fig. 1

is chiefly stimulated by a region of the spectrum of very low visibility, about half of the blue present in white being due to radiation of wave-length below ·45 μ. It is evident from Fig. 1 that, unless spectrophotometric measurements are of quite high precision right down to about ·4 μ, serious error may be made in calculating the amount of blue in the resultant colour.

This difficulty has not been specifically dealt with by previous writers on the

* *Journ. Franklin Inst.* 195 (1923) 23.

physical basis of colour, but it is a serious obstacle to the employment of spectrophotometric data in colour calculations, except for colours from which the blue end of the spectrum is excluded, i.e. saturated reds and yellows.

With the Koenig-Martens instrument, under ordinary conditions of use with a heterochromatic source of light, it is difficult to make observations with any claim to accuracy below $\cdot 45\mu$ owing to the faintness of the field illumination. Priest, McNicholas, and Frehafer* give data obtained with such an instrument used under the most favourable conditions and claim reasonable accuracy down to $\cdot 43\mu$, "provided the transmission is not changing rapidly with wave-length," that is, provided wide slits can be used. Even this leaves quite an important portion of the blue sensation curve out of account.

Apart from the question of field brightness the instrument has other important defects in design. The wave-length variometer is of a crude type and requires frequent recalibration owing to the point of the micrometer screw wearing into the surface of the hardened steel plate against which it operates. The scale attached to the rotating nicol is of small diameter, and one vernier only is fitted, thus leaving the readings subject to centering error. In general, the instrument is not suited, and was not, in the writer's view, ever intended, for work of the highest precision.

The other spectrophotometer is also wasteful of light. In this instrument the field of view is in the plane of the spectrum, a small region of which is visible between two shutters in the eyepiece. Precision of setting is impossible with a system of this kind, particularly where the absorption of the specimen under test is varying rapidly with wave-length. Further, the principles on which the instrument is constructed render it liable to a variety of constructional defects which may easily lead to gross errors over and above those due to insensitivity.

For these reasons it was found necessary to design spectrophotometric equipment on entirely fresh lines, and the apparatus described below is the result. This embodies a number of minor modifications incorporated fairly recently, but, in its essentials, the apparatus has been in use with satisfactory results for several years.

General Description

A diagrammatic plan of the complete apparatus is shown in Fig. 2, and a photograph of it in Fig. 3. It is difficult to obtain a photograph of such a group of apparatus which shows all the essential features, but the general lay-out of the equipment can be seen from Fig. 3.

A Hilger constant deviation spectrometer is provided with a second collimator C_2 (Fig. 2) mounted parallel to the ordinary collimator C_1. A photometric prism P is mounted as shown in relation to the collimators. This prism consists of a rhomb $ABCD$ (Fig. 4) of which all four faces AB, BC, CD, and DA are polished, to which an isosceles prism ABE is attached. The two surfaces at AB are in optical contact over part of their area and out of contact over the remainder, as

* "Some tests of the precision and reliability of measurements of spectral transmission by the Koenig-Martens Spectrophotometer." *Journ. Opt. Soc. Amer.* 8 (1924) 201.

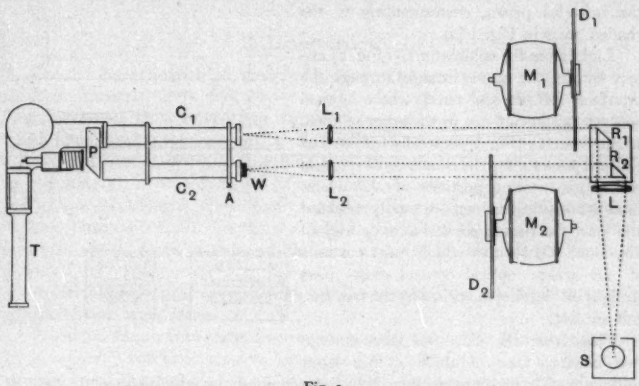


Fig. 2

Fig. 3

shown in Fig. 4 (*a*), where the unshaded portions represent regions of optical contact. This is accomplished by graying portions of the hypothenuse surface of the isosceles prism, corresponding to the shaded areas in Fig. 4 (*a*).

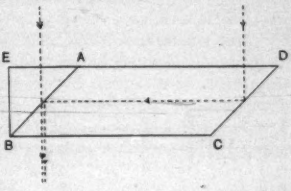


Fig. 4

Light from the collimator C_1 (Fig. 2) enters by *EA* and passes straight through the interface *AB* at the parts where optical contact exists, but not in the other regions. Light from C_2 (Fig. 2) is totally reflected at *DC* and passes along the rhomb until it meets *AB*. Rays meeting portions of *AB* where there is no optical contact are totally reflected and leave the rhomb parallel to their original direction. Those rays which meet portions of *AB* where optical contact exists pass straight on, leaving the prism by the face *EB*, and are lost.

Thus from the side *BC* there emerge two beams. One of these comes from collimator C_1, its cross-section being determined by the unshaded area of Fig. 4 (*a*); the other comes from C_2, its cross-section being determined by the shaded area of Fig. 4 (*a*). If the collimators are parallel, these beams are parallel and, after passing through the dispersing prism and the lens of the telescope *T* (Fig. 2), form two coincident spectra in the focal plane of the latter.

The eyepiece of the telescope is replaced by a slit. On looking through this slit the observer sees a field, shaped like Fig. 4 (*b*), which is simply Fig. 4 (*a*) foreshortened as seen from an obliquity of 45°, the unshaded area being illuminated by light from C_1 and the shaded area by light from C_2. The illumination is monochromatic light of the wave-length determined by the part of the spectrum falling on the ocular slit. This is varied in the ordinary way by means of the wave-length drum of the spectrometer.

Two strips of thin parallel glass, rather larger than the interior rectangles of Fig. 4 (*b*), are attached to the faces *EA* and *AD* in such positions that the portions of the respective beams which go to illuminate these rectangles must pass through the strips. In this way we obtain the Lummer-Brodhun equality-of-contrast field, as used in ordinary photometry. The advantages of this field for spectrophotometry are discussed later.

All three slits open symmetrically, so that the wave-length calibration is not affected by varying their widths.

An adjustment is provided for setting the axis of C_2 so that the spectrum it produces exactly coincides, as regards wave-length, with that from C_1.

This part of the apparatus is similar in principle to the Lummer-Brodhun spectrophotometer*, differing only in the use of a constant deviation spectrometer,

* *Z. f. Instrk.* 12 (1892) 132.

and the form of the prism P, which permits the collimators C_1 and C_2 to be arranged parallel instead of at right angles to one another.

Illumination

For the determination of spectrophotometric transmission curves of slabs of absorbing material it is desirable to arrange matters so that the same source illuminates both fields in order to obviate the necessity of careful voltage control, which is required if separate sources are used. The source S (Fig. 2) consists of a 12-volt 24-watt gas-filled lamp having a straight spiral filament about a third of an inch long. It is situated at the focus of an achromatic lens L of 8 cm. aperture and 35 cm. focal length. Two totally reflecting prisms R_1 and R_2 deflect portions of the collimated beam in directions parallel to the axes of C_1 and C_2. Achromatic lenses L_1 and L_2 focus these beams to form images of the filament on the slits of C_1 and C_2.

A variable resistance in series with the lamp enables the field brightness to be adjusted over a wide range.

When it is required to make spectrophotometric comparison of separate sources, R_1 is removed and arrangements are made so that the slit of C_1 is illuminated alternately by the two sources to be compared, S being employed as the comparison lamp in a substitution method. The arrangements required vary with the size and nature of the sources to be compared.

The great majority of spectrophotometric measurements, however, consist of determinations of transmission factors, and for these the normal arrangement is that of Fig. 2. Since the lamp may be considerably underrun for the great bulk of the observations, it may be considerably overrun, when required, without inconveniently shortening its life. It is our practice when working in the violet region, or in any other region, if, owing to the absorption of the specimen under test, the field brightness is low, to run the lamp at a colour temperature well over 3000° K.

The Measuring Apparatus

The basis of measurement in most spectrophotometers is the law governing the transmission of polarized light through a variously orientated analyser. Considerable experience in the use, design, and construction of instruments employing polarization for the variation of intensity has led the author to the view that the method is entirely unsuitable for use in spectrophotometry. Apart from the 60 per cent. or more loss of light inevitably associated with the use of nicol prisms, there are errors due to defects of construction and mounting which do not appear to be generally understood by makers of optical instruments, and even when understood, require considerable precaution to eliminate.

It was therefore decided not to employ the polarization method, despite its great simplicity and convenience in use, but to make the measurements depend on the law of the sector disk.

It has been shown by Hyde* that Talbot's law holds, to within the accuracy of the best photometric measurements, down to quite small angular openings. Whether or not the law fails for very small openings is not easy to determine, owing to the difficulty of accurately evaluating the openings, but in any case this is immaterial as, by the procedure adopted here, quite low intensities may be dealt with without using disks with excessively small openings.

Variable sectors were first tried, one of a commercial pattern and another designed and made at the Laboratory, but it was ultimately decided to discard these and employ sectors of fixed opening. Such sectors form invariable units which can be accurately measured up and checked in various ways.

A series of 13 sectors, 12 inches in diameter, and with angular openings as listed in the following table, are employed. These are made so that they may easily be fitted to one or other of the motors M_1 or M_2 (Fig. 2).

Series No.	Constants of Sectors		Approximate ratio of each factor to next higher
	Total angular opening ($=\theta$)	Transmission factor ($=\theta/360$)	
1	324°	·900	—
2	292	·811	·9
3	263	·731	·9
4	238	·661	·9
5	216	·60	·9
6	194	·539	·9
7	180	·50	·93
8	162	·45	·9
9	81	·225	·5
10	36	·100	·45
11	18	·050	·5
12	7·2	·020	·4
13	3·6	·010	·5

It will be noted that these sectors fall into two groups, a closely graded group in which each unit transmits about nine-tenths as much as the next higher, and a more widely spaced group, in which the fraction is in the neighbourhood of a half. Had the sectors been made with a view to the present purpose only, values would have been chosen for the smaller angle sectors in closer accordance with the 50 per cent. spacing, but it was desired to have units of ·1, ·05, ·02, and ·01 for certain other uses, and these are sufficiently near the proper spacing for all practical purposes.

The sector equipment is shown in Fig. 5, from which the essential details can be gathered. Each disk has an accurately cut central hole which fits without play on a boss carried by the axle of the motor. It is clamped in position by a nut with an interrupted thread. A small hole in the disk registers with a pin which projects from the back plate of the axle fitting in order to prevent slip and possible

* *Bull. Bur. Stand.* 2 (1906) 1.

loosening of the nut, due to the inertia of the disk during acceleration or deceleration.

To remove one disk and fit another is the work of a few seconds.

The motors employed are 1/10 H.P., 2000 ~, D.C. shunt-wound motors with ball bearings. In order to get smooth vibrationless running it was found necessary to replace the original bearings by new ones.

The power to the motors is controlled by a master switch. When this switch

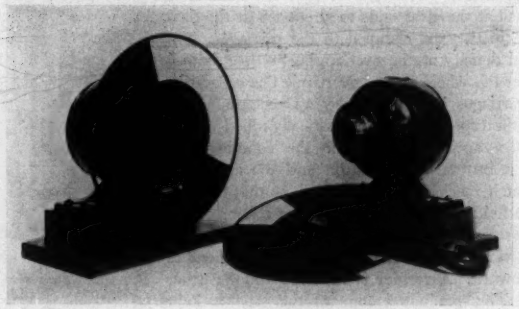


Fig. 5

is closed, the field circuits of both motors are energized. The armature of each motor is connected to a two-way switch. In one position this switch connects the armature, through a rheostat, to the power supply. In the other position of the switch, the armature is disconnected from the power and is short-circuited, thus introducing a powerful electromagnetic braking action which brings the motor to rest in a few seconds. These switches, one for each motor, are situated conveniently to the hand of the observer.

The two motors are mounted on a board at a suitable height above the table to bring the axles on a level with the optical system. To prevent vibration reaching the optical parts, a double system of shock absorbers is employed. The base block of each motor is separated from the supporting board by pieces of stout pressure-tubing (external diameter 1 inch, internal ·25 inch), and pieces of similar tubing are inserted between the board itself and the bricks which support it at the proper height above the table. This double set of cushion "tyres" damps out most of the vibration which would otherwise be transmitted through the table to the various parts of the apparatus.

As will be seen later, by a proper choice of sectors in the two beams, we can always bring the two halves of the photometric field to within 5 per cent. of equality of brightness. To bridge the outstanding gap, and to provide a convenient means of setting, photometric wedges *W* (Fig. 2) in front of the comparison slit are used.

This piece of apparatus is shown in Fig. 6. Two neutral wedges*, 10 inches long, are mounted on carriages which slide on a stout rod. The carriages are attached to an endless chain which passes round two cog wheels. The axle of each cog wheel carries a milled head, and by means of either of these the carriages can be made to approach or recede, thus varying the amount of overlap of the two wedges. The density† of these wedges varies uniformly from something quite small at the clear ends to about 1·8 at the dark ends, where they are clamped to the carriages. The combined density of the overlapping wedges is uniform over the whole area of overlap. The separation of the carriages is measured by a Chesterman steel tape, of the type which is automatically rolled up, by means of a spring roller inside the container, on pressing a button. This button and the associated spring catch mechanism is removed, so that the tape is always held in tension by the spring roller.

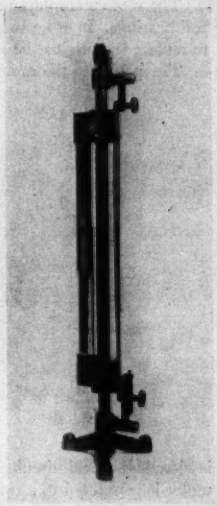


Fig. 6

The free end of the tape is attached to one of the carriages while the container is mounted at the end of the framework. A vernier is mounted on the other carriage. The graduated edge of the tape is kept against the edge of this vernier by means of lightly pressing guides under which the tape slips easily as the carriages move. The readings of the tape and vernier measure the separation of the carriages to within a tenth of a millimetre, the value so obtained being unaffected by backlash in the mechanism for moving the carriages.

The wedge apparatus can be calibrated *in situ* by measuring with it the transmissions of a series of sectors or sector combinations as described later. Fig. 7 shows the calibration curve of a particular pair of wedges for a wave-length of ·57 μ. It will be observed that the linear relationship between density and scale reading is very closely realized. Such wedges are not strictly neutral, the density increasing gradually from the red to the blue end of the spectrum. To determine the necessary correction to the values given by Fig. 7 to make them apply to other wave-lengths, it is only necessary to make readings throughout the spectrum on one sector (preferably one of fairly low transmission), for if D_1 and D_2 are the densities for unit thickness of the material for wave-lengths λ_1 and λ_2, nD_1 and nD_2 are the corresponding densities for n units of thickness. The ratio of the densities nD_2/nD_1 is not affected by the value of n, and is therefore the same for all thicknesses of the

* In these wedges the absorption is due to finely divided lamp-black suspended in gelatine. They were supplied from stock by Messrs Sanger-Shepherd.

† $D = \log_{10}(1/a)$, where a is the transmission factor.

material. Thus from measurements of the variation of density with wave-length at one density level correction factors to correct the densities given by Fig. 7 to other wave-lengths can be deduced. This correction curve is shown in Fig. 8.

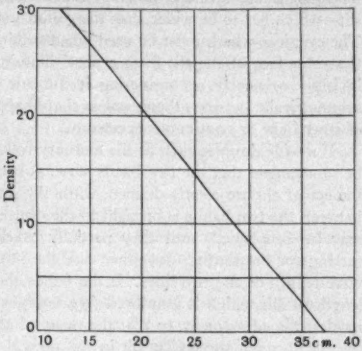


Fig. 7

It will be noted that the range of transmission covered by the wedges is very great, transmissions less than 0·1 per cent. being easily reached. For approximate determinations in which the highest accuracy is not required the wedges alone may be used for all measurements. The calibration cannot, however, be regarded as sufficiently constant for very accurate work involving a large density difference owing to the difficulty of keeping the wedges absolutely clean. It is better, therefore, to employ them over small ranges only, to fill in the gaps between the various sector combinations. Even for this purpose it is advisable to use wedges of reasonably large density range rather than a less steeply graded pair. In the first place, if the constants of the wedges are determined over a long range, the experimental errors of the calibration are rendered negligible over the shorter ranges to be employed in their subsequent use.

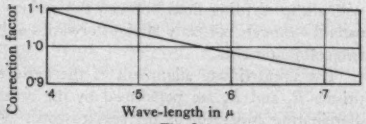


Fig. 8

Further, the use of such wedges enables the initial illumination level of the comparison side to be set to any desired value, while still only making measurements over a small range in the neighbourhood of that value. This is sometimes of great convenience as will be evident when the method of measurement is described.

Adjustments

The Wave-length Setting

This is effected by illuminating the slits with suitable monochromatic light. The prism is adjusted on its table so that the wave-length drum reads correctly for light from C_1 (Fig. 2). The second collimator C_2 is then adjusted, by means of a screw A in one of the supporting brackets, until the wave-length reads correctly for it also.

It may be useful to mention here that the adjustment of any instrument of this type, in which a slit is situated in the focal plane of the telescope, is most easily

and accurately performed if a wide doublet, such as the yellow lines of mercury, is employed instead of a single spectral line. Using the latter it is necessary to set the single image of the collimator slit symmetrically between the jaws of the ocular slit—which has to be wider than the collimator slit in order that this may be done. The eyepiece which must be used when making the adjustment usually so shields the outer face of the slit from general illumination that the jaws are either quite invisible or nearly so, rendering it difficult to see when the spectrum line is symmetrically between them, unless there happens to be a fairly strong background of stray light or continuous spectrum.

If a wide doublet such as the mercury yellow lines be used, the slit widths can be so arranged that the two bands serve as backgrounds against which the edges of the ocular slit are clearly defined, while the setting is made so that the black strip between the two bands is brought to the centre of the slit. Alternatively the bands may be broadened until they partially overlap, the strip of double brightness serving for the setting. In either case the setting made corresponds to the mean wave-length of the two lines. If the bands show appreciable curvature within the length of slit which is employed (see later), allowance must be made for this in making the adjustment, so that the mean of all the wave-lengths which can enter the eye through the ocular slit in the normal use of the instrument may be that indicated on the drum.

Adjustment of Illumination

In order that the two portions of the field of view may be uniformly illuminated, with sharp dividing lines between the various areas, it is necessary to make very careful—though perfectly straightforward—adjustments of the illumination of the two collimator slits.

The approximate alignment of the various parts and the adjustment of the prisms R_1 and R_2 are performed by the ordinary methods used in aligning the illuminating apparatus of any spectroscope. The precise adjustment of the focus and position of the images formed by L_1 and L_2 is of the greatest importance, and for this it is desirable that the stands supporting L_1 and L_2 should be provided with fine adjustments for longitudinal, transverse, and vertical motions. Those shown in Fig. 3 were not specially made for this apparatus and do not have longitudinal adjustment other than is obtainable by moving them bodily. Special stands having all the adjustments mentioned would be preferable. Consider first the adjustment of L_1. The collimator slit is reduced to narrow dimensions and L_1 is adjusted longitudinally until, on traversing the image across the slit by means of the transverse adjustment, the field darkens or brightens uniformly all over, or as nearly so as possible. This gives the correct position of focus. The height of L_1, and consequently the part of the collimator slit covered by the image of the filament, should then be adjusted until the spectral band formed in the plane of the ocular slit occupies the central portion of the latter. The lens L_2 is adjusted in a similar manner to get correct focus and also to get the spectral band from C_2 exactly superposed on that from C_1. This last adjustment is facilitated by examining the

ocular slit with an eyepiece. It is very important, as, if there is any vertical displacement between corresponding points of the two spectra, parallax effects are introduced which destroy the appearance of the dividing lines, the two fields either overlapping slightly or being separated by a black line.

When the foregoing adjustments have been made, the length of the ocular slit should be reduced by means of a V-slider, as ordinarily fitted to spectroscope slits, so as to cut off the extreme top and bottom of the spectrum. This prevents variation of the relative brightness of the two fields on moving the eye up and down. Such variations are difficult to avoid if the light from the extreme ends of the filament of the lamp is allowed to reach the eye, unless the vertical registration of the two spectra is absolutely accurate.

Method of Use of Apparatus

We shall first consider the procedure followed in determining the transmission data for a plane parallel slab of material, which is the measurement most frequently required.

The specimen is placed in the collimated portion of the direct beam, i.e. between L_1 and R_1. It is adjusted to be normal to the beam by observing when the patch of light reflected from its surface falls exactly on the prism R_1. In order that this adjustment may not have to be made repeatedly, the stand carrying the specimen is mounted on a sliding carriage on an optical bench so that the specimen may be moved in or out of the beam without affecting its adjustment. This bench can be seen in Fig. 3. The type of specimen support employed depends on the nature of the specimen, and is not included in the photograph.

In the case of small specimens which are not large enough to intercept the whole of the effective portion of the collimated beam, these may, if thin, be mounted just in front of the slit, although this situation should not be used except when unavoidable.

If the transmission for the wave-length at which a measurement is being made is fairly high, say, above 45 per cent., it is only necessary to use one of the sector disks. The first eight sectors cater for the range 100 to 45 per cent. with gaps of approximately 10 per cent., so that a sector can be found for which the transmission is within 5 per cent. of any required value between these limits.

The specimen is placed in position and the fields are equalized by setting the wedges. Let I_1 and I_2 be the full luminosities of the direct and comparison fields in the absence of either specimen or wedges, and let α be the transmission factor of the specimen and w the transmission factor of the wedges when the setting is made. Then

$$I_1\alpha = I_2 w \quad \text{or} \quad \alpha = w\frac{I_2}{I_1}.$$

A blank observation is then made with the specimen removed and the sector D_1 (Fig. 2) rotating, the wedge setting being altered to equalize the fields. If d_1 is the transmission factor of the sector, and w' is that of the wedges as now set,

$$d_1 = w' I_2 / I_1,$$

whence

$$\alpha = d_1 w / w'.$$

If the proper sector is chosen, w/w' will not differ from unity by more than 5 per cent. or so, so that the accuracy of the wedge calibration becomes relatively unimportant.

When the transmission is below 45 per cent., it is in general necessary to use both sectors. The gaps between adjacent sectors below this value are approximately five times as large, each sector transmitting about half as much light as the next higher. The procedure is as follows. The blank setting is made with the specimen absent and the nearest sector of *higher transmission than the specimen* rotating in the direct beam. Let d_1 be the transmission of this sector, and let w' be the transmission of the wedges as set. Then

$$d_1 I_1 = w' I_2.$$

Insert specimen and stop the sector in the direct beam; insert in the comparison beam that sector which most nearly equalizes the fields; then complete the equalization by means of the wedges. Let d_2 be the transmission of the sector and w that of the wedges, while α represents as before the transmission of the specimen. Then

$$\alpha I_1 = w d_2 I_2,$$

whence

$$\alpha = d_1 d_2 w/w'.$$

The effective value of the sector combination as thus used is the same as that of a single sector of transmission value $d_1 d_2$.

Since d_1 need never be more than about twice α, provided the latter is not less than ·5 per cent., d_2 will be between 100 per cent. and 50 per cent., and the second sector belongs to the closely graded series, so that the whole range from 100 to ·5 per cent. can be covered by a series of fixed points, each corresponding to a transmission about ·9 times the next.

It is not desirable to construct a single sector with a transmission of less than 1 per cent. As a matter of fact neither the 1 per cent. nor the 2 per cent. sectors were cut directly to size from the solid disk. Rather larger openings were cut, and separately machined jaws were bolted and soldered in position after adjustment to the correct angle under a microscope. With much smaller openings than those, it becomes difficult to ensure that the edges are sufficiently truly radial to render the photometric value of the sector independent of its position in the beam. We can still, however, carry the system of measurements below ·5 per cent., without increasing the gaps between the fixed points, by varying the procedure slightly so as to introduce a third sector.

As before let the blank setting be made with a sector of transmission d_1 in the direct beam, w' being the wedge transmission. Then

$$d_1 I_1 = w' I_2.$$

Let the other setting be made with the d_2 sector in the comparison beam and both the specimen and a sector of transmission d_3 in the direct beam. If w is the wedge factor in this case,

$$d_3 \alpha I_1 = d_3 w I_2,$$

whence

$$\alpha = \frac{d_1 d_2}{d_3} \cdot \frac{w}{w'}.$$

The effective value of the three sectors as thus used is that of a single sector of transmission $d_1 d_2/d_3$. If d_3 is chosen from the closely graded series, d_1 and d_2 being both from the widely graded series, we can obtain close graded spacing right down to ·01 per cent.

The introduction of the third sector increases, though only slightly, the time involved in a complete measurement, since the disk in the direct beam has to be changed, instead of only stopped or started, each time the specimen is inserted or withdrawn. It is preferable, therefore, except for particular purposes, to use the two-sector procedure even below ·5 per cent., relying on the wedges to cover the gaps of 25 per cent. or thereabouts which may exist between the desired value and that of the nearest two-sector combination.

In any case, in regions where the transmission of the specimen is varying fairly rapidly with wave-length, a gap between the transmission to be measured and that of the nearest sector or sector combination can always be avoided by choosing a suitable wave-length at which to make the determination. In fact, when making observations on the sloping sides of absorption bands, it is sometimes advantageous to use the wave-length drum for setting, determining the wave-length for a given transmission instead of the transmission for a given wave-length. The only precaution required in this procedure is due to possible variation with wave-length of the blank reading. It is necessary first of all to determine approximately the wave-length corresponding to a certain transmission as given by a particular arrangement of sectors. Then the specimen should be removed and the blank setting made at this wave-length. The specimen is then re-introduced, the necessary changes in the sectors made to give the required transmission, and the final settings made by means of the wave-length drum, the wedges remaining as set for the blank reading. In this way points are obtained depending on the sectors only and entirely independent of the wedge calibration.

To extend the scale below ·01 per cent. is rarely necessary, but can be done by relying on the wedges for a still greater range. The accuracy of the wedge calibration is more than sufficient for all measurements which have to be made at such opacities.

There are certain points of technique in the use of the apparatus which are of considerable importance. The slits of the two collimators being separately variable, a wide range of adjustment of the relative field illumination is possible quite apart from the measuring equipment. In general the slits of C_1 (Fig. 2) and T are set to such widths as considerations of spectral purity may require, the permissible widths being least where the absorption is varying most rapidly with wave-length. Also, other things being equal, wider slit widths are permissible at the blue end of the spectrum than at the red, owing to the variation of dispersion with wave-length. These slits should always be reduced, keeping them approximately equal in width, until no change in the value obtained for the transmission takes place on still further reduction.

The slit of the comparison collimator C_2 is subject to no such limitations, and may be set to any width necessary to bring settings to a convenient part of the

wedges. It will be noted that neither accuracy of wave-length setting nor homogeneity of wave-length is essential on the comparison side, which has merely to provide a comparison field of identical colour to the test field. The apparatus employed to vary the intensity of the comparison field being practically neutral in its effective absorption, the readings are not affected by the width of the comparison slit so long as this is the same for the measurements with and without the specimen.

Advantage should be taken of the separate adjustment of the comparison slit to alter slightly the region of the wedges employed, when repeating observations, as this eliminates any effects due to irregularities in the wedges which are not accounted for in the calibration.

In the case of specimens which have not been worked to fairly accurate parallelism, errors of serious magnitude may be caused by the prismatic refraction shifting the image of the source so that a different part of the latter falls on the collimator slit. This would be of no consequence if a source were available which had a uniform intrinsic brightness over a fairly large area, but of the commercially available sources of high intrinsic brightness there is none with this property. The difficulty is obviated in the present apparatus by causing the image to pass across the slit, by means of the transverse adjustment of the lens L_1, until the position of maximum brightness is reached. If this is done for the readings with and without the specimen any displacement due to the latter is automatically compensated. The process of adjusting for maximum brightness for each observation is analogous to the adjustment for minimum deviation in refractometric work. In each case the required quantity passes through a stationary value, and the adjustment is easily made with the necessary accuracy. As a safeguard against the possibility of an occasional error it is desirable to perform the maximum brightness adjustment as part of the routine of each observation and not only on introducing or removing the specimen.

When working near either extremity of the spectrum, and sometimes in other circumstances, there is a considerable amount of stray light, due to other and brighter parts of the spectrum flooding the field. This can be eliminated by the use of suitable gelatine filters placed in front of the eyepiece. Filters should be selected which are as transparent as possible to the region of the spectrum in which measurements are being made, while cutting out the remainder.

With a system of the type employed in this apparatus there is no focussing device. It is convenient to have a few trial case spectacle lenses of low power, one of which may be fitted in front of the observing slit. This enables an observer to get sharp definition of the field with comfortable accommodation.

In employing the apparatus for comparing the energy distributions of two sources, the lamp S (Fig. 2) becomes a comparison lamp only, and must be run under steady and measured voltage conditions. The prism R_1 is removed, and suitable optical arrangements, depending on the nature of the sources, must be made so that either source can be focussed on the slit of C_1. Each is in turn compared with S, the use of the sectors and wedges being similar to that described for measuring transmission factors.

Calibration of Sectors and Wedges

The procedure involved in calibrating the measuring equipment is very similar to the procedure described above for its subsequent use. As regards the sector disks, it will be evident that disks of fairly large transmission can be made with far greater accuracy than can possibly be checked by photometric measurement. The angles can be cut on a milling machine to within 5 minutes of their nominal value. A 5 per cent. disk has its two angular openings of 9° (= 540 minutes), so that such a disk can be regarded as almost certainly accurate to 1 per cent. of its value without any check whatever. By measurement of the angle on a suitable goniometer, the value can be determined to within about 1 minute. It is simpler, however, in the case of those sectors which are small enough to justify calibration, to calibrate them photometrically rather than mechanically, since this eliminates any question of the validity or otherwise of Talbot's law for small openings.

The following method consists in stepping down from values large enough to be assumed with certainty to the smaller values. Suppose it is desired to determine the value of a sector D of nominal transmission d. Select two sectors D_1 and D_2 having known transmissions d_1 and d_2 such that $d_1 d_2 = d$. Set the wedges to equalize the fields when D_1 is in the direct beam. Let w be the wedge reading. Replace D_1 by D and put D_2 in the comparison beam. Let w' be the wedge reading on again equalizing the fields. In the first case $d_1 I_1 = w I_2$, and in the second case

$$dI_1 = w' d_2 I_2,$$

whence

$$d = d_1 d_2 w'/w.$$

If $d = d_1 d_2$ exactly, $w' = w$ and the wedge reading is the same in both cases. If d differs slightly from its nominal value a very small alteration in wedge reading, for which a crude knowledge of the wedge calibration is adequate, is required. Since D_1 and D_2 are not in simultaneous operation, the same sector may, if required, be used for each. In this case $d_1 = d_2 = \sqrt{d}$.

If the sectors are made with reasonable care any check on the 10 per cent. or larger sectors should be quite superfluous. If desired, however, the 10 per cent. disk can be checked against the 45 and 22·5 per cent. disks, the product of these being 10·125 per cent., which is sufficiently near for the purpose. The 5 per cent. disk can be checked with those of 10 and 50 per cent. (product 5·00 per cent.) or by using the 22·5 per cent. disk first as D_1 and then as D_2, in which case the equivalent value is 5·06 per cent. The 1 per cent. sector can be checked in the same way by using the 10 per cent. disk first as D_1 and then as D_2, which gives an equivalent value of 1 per cent. There is no combination of larger sectors (in the series actually constructed) which gives the nominal equivalent value of 2 per cent., but this disk can be checked against the 1 and the 50 per cent., once the former has been established.

Alternatively, the process may be performed in one measurement by the procedure involving, in its general form, a third known sector D_3, of transmission d_3.

Let w be the wedge reading required when D_1 is in the direct beam and D_3 is in the comparison beam. Then

$$d_1 I_1 = w d_3 I_2.$$

Then, as before, let w' be the wedge reading when the sector under test, D, is in the direct beam and the sector D_2 is in the comparison beam. Thus

$$d I_1 = w' d_2 I_2,$$

whence

$$d = \frac{d_2 d_1}{d_3} \frac{w'}{w}.$$

In such a case the wedge reading will remain unaltered if $d = d_2 d_1 / d_3$.

Thus, if there are not two sectors such that their product $d_2 d_1$ has the required value, it may be possible to find a third sector D_3 such that $d_2 d_1 / d_3$ has the required value. As in the simpler case in which two known sectors only are involved, the same sector may be used, if required, for D_1 and D_2. In this way we may check the 2 per cent. disk by using the 10 per cent. for D_1 and D_2 and the 50 per cent. for D_3.

Obviously the method above outlined for calibrating sector disks of small photometric value is generally applicable for all purposes for which such disks may be used. The measurement may, if desired, be carried out on a photometer bench, the two motors being mounted on opposite sides of the photometer head, small movements of one or other of the lamps taking the place of the wedge adjustment employed in the present equipment. The procedure overcomes entirely the practical difficulties involved in applying the inverse square law over a large range of lamp movement which are encountered in the direct calibration of a single sector on a photometer bench.

The calibration of the wedges in terms of the disks used singly and in combination is quite straightforward. The slit widths should first be set so that the fields are equalized with the wedges overlapping as little as conveniently possible, and with a sector in the same beam as the wedges. The sector is then stopped and the wedges re-set. This gives the difference in wedge reading corresponding to the effective absorption of the sector. In this way the calibration can be carried to a density difference of 2, equivalent to a transmission ratio of 1 per cent. To go below this we must use a combination of sectors. As before set the slit widths so that a balance is obtained at the convenient zero setting of the wedges with a sector in the same beam as the wedges. Let d_2 be the transmission of the sector and w that of the wedges. Then

$$w d_2 I_2 = I_1.$$

Make another setting w' with this sector removed and one inserted in the other (direct) beam. Let d_1 be the transmission of this disk. Then

$$w' I_2 = d_1 I_1,$$

whence

$$\frac{w'}{w} = d_1 d_2.$$

In this way the difference in wedge readings corresponding to a transmission ratio given by the product of the factors for any two sectors, or the square of any one factor, may be obtained.

Summary of Features of Apparatus

Light Efficiency

The chief aim in designing this equipment was to avoid all unnecessary loss of light, in order to facilitate measurements in those parts of the spectrum where visibility is low. There are certain optical parts essential to any spectrophotometer. Firstly, there is a spectroscopic system comprising two lenses and a prism. In addition to this there is a device for producing a juxtaposed field and, external to the instrument, some means of dividing the light from the source into two separate beams. These should be collimated for part of their lengths in order that considerable thicknesses of material may be tested. It will be observed that in the direct beam, Fig. 2, there are no optical parts other than the minimum number which can fulfil the above mentioned functions. Further, the comparison slit being separately adjustable to compensate for the appreciable absorption of the wedges at their lightest convenient setting, and not being limited in width by the same considerations which limit the slit width of C_1, the initial equalization of field brightness can always be made with the latter slit as wide as purity considerations permit, thereby enabling the maximum illumination to be obtained which is practicable with any spectrophotometer using a gas-filled lamp as the source of light.

Needless to say, except at the ends of the spectrum, or when measuring very low transmissions, the maximum field brightness would be too dazzling for photometric observations to be made at all. Ordinarily, the field brightness is reduced to a convenient value by the variable resistance in the lamp circuit, which should have sufficient range to reduce the filament almost to redness.

Lummer-Brodhun Field

The Lummer-Brodhun contrast pattern field is not usual in spectrophotometers although its advantages for this purpose are even greater than for the ordinary photometric work in which it is almost universally employed. Actually, at medium or high field brightnesses it is difficult to get the full advantage of the contrast field, simply because it is not so easy to get the whole area of the field absolutely uniform in brightness as it is in the case of an ordinary bench photometer where a diffusing screen is used behind the photometric cube. It is at low luminosities, where the Fechner fraction becomes high and the sensitivity to brightness difference becomes low, that the great advantage of the contrast setting is obtained. For instance, suppose the conditions to be such that the eye can just detect a difference of 8 per cent. in brightness. With an ordinary simple comparison field there would be a range of 8 per cent. above and below the equality point within which satisfactory settings could be made. With the contrast pattern field, however, both contrast patches would just be visible at the correct setting. A little either way and one or other of the patches would disappear. In fact the sensitivity of setting does not fall off appreciably so long as both contrast patches can be seen at the

same time. For still lower brightnesses, at which the sensitivity is so low that a range exists within which neither patch can be seen, we still obtain an advantage from the contrast patches, since it is evident that one or other will become visible when the fields are 8 per cent. less out of balance, either above or below, than would be required to produce a visible difference without them.

The Method of Measurement

The use of a closely graded series of sector disk units, in conjunction with a pair of photometric wedges for setting, provides a convenient and accurate basis for the measurements which has none of the disadvantages attached to polarization methods. The device of employing two sector equipments, one in each beam, enables transmissions as low as ·01 per cent. and less to be referred directly to the sector law without the use of sectors of excessively small opening, and provides also an easy and convenient method of measuring the photometric value of the small angle sectors themselves in terms of the larger units.

Another important feature of the method is that the two settings involved in determining a transmission factor, namely those with and without the specimen in position, are made at similar field brightnesses, the disparity never being greater than two to one. This is of great importance in measuring very low transmissions, as it avoids the strain on the eyes, and other causes of inaccuracy, which result from making alternate measurements at widely different field brightnesses.

Adjustment for Maximum Brightness

The introduction of this adjustment into the technique of spectrophotometry, by eliminating errors due to the joint effect of non-uniformity of intrinsic brightness of the source and prismatic displacement of the image, overcomes what has always been a serious difficulty in using an image of a source to illuminate the slit or slits. Such a device can only be used where, as in the present equipment, separate slits and separate optical systems are employed for the two beams.

ADDENDUM ON CHOICE OF SECTOR DISKS FOR USE IN COMBINATION (added 18th May, 1925)

The following notes may be of interest to those who wish to use sector disks in the manner described in this paper, and who may be desirous of employing the minimum number of disks which will serve the purpose. It is required to have a series of disks of such transmissions that used singly, or in the combinations explained in this paper, a series of equivalent transmission values, each of which bears a constant ratio, ρ say, to the next in order, is obtainable.

Employing two sectors of transmissions ρ^{N_1} and ρ^{N_2}, we can obtain equivalent values of $\rho^{N_1+N_2}$ or $\rho^{N_1-N_2}$ by the two-sector procedure: by the three-sector procedure we can obtain equivalent values of $\rho^{N_3\pm(N_1-N_2)}$ from three sectors of which N_1, N_2, and N_3 are the individual indices.

A single series of sectors for which the indices are

$$1, 2, 4, 7, 11, 16, \ldots 1 + \tfrac{1}{2}r(r-1)$$

offers some advantages, but any series of this type in which progressively increasing gaps occur between successive individuals has the great disadvantage that it becomes impossible to fill up gaps which arise comparatively early in the series except by combinations of members of excessively high index.

For this reason it is better to discard series of this type and to construct the disks in two or more groups, each having a constant difference in the indices of its members. For instance, a grouping such that the indices are

$$1, 2, 3, \ldots m$$

$$2m, 4m, 6m, \ldots 2m^2$$

enables all sectors to be checked by the method of the paper and in use gives every integral power of ρ in the series of equivalent values up to $\rho^{m(2m+1)}$ by means of the two-sector procedure.

A given range can be covered by even fewer sectors by dividing these into three groups, provided the three-sector procedure may be admitted in the normal use of the equipment. For instance, with a grouping such that the indices are

$$1, 2, 3, \ldots m$$

$$2m, 3m, 4m, \ldots nm$$

$$2mn, 4mn, 6mn, \ldots 2mnp$$

all sectors may be checked by the two-sector procedure but the three-sector procedure is necessary in use to obtain many of the intermediate powers.

The third group may alternatively have the indices

$$3mn, 5mn, 7mn, \ldots mn(2p+1)$$

in which case the three-sector procedure is necessary in checking the sectors as well as in their subsequent use.

In the first case it is advantageous to arrange the grouping so that $m = n = p$ or $p + 1$ and in the latter case $m = n = p + 1$. The highest index reached without gap is $mn(2p+1)$ in the first case and $2mn(p+1)$ in the latter.

These formulae are useful if the ultimate number of disks to be used is stipulated.

A series differing slightly, but suitable for extension if desired, is as follows:

Total number of disks	Values of N	Highest consecutive index in series of equivalent values
6	1, 2, 3, 6, 9, 27	36
7	1, 2, 3, 6, 9, 27, 45	54
8	1, 2, 3, 6, 9, 27, 45, 63	72
9	1, 2, 3, 6, 9, 27, 45, 63, 81	90

If ρ is taken as ·9, and it is desired that the smallest sector constructed shall transmit about 1 per cent., seven disks will serve, since $\cdot 9^{45}$ is about ·0087.

There are, however, practical disadvantages for work such as that described in the present paper in introducing the three-sector procedure in the normal use of the apparatus, and a two-group system, while requiring more disks, is to be preferred. For the requirements stated above, twelve disks are the minimum. They may be grouped in either of the following ways:

$$N = 1, 2, 3, 4, 5, 6;\ 12, 18, 24, 30, 36, 42$$

or $$1, 2, 3, 4, 5, 6, 7;\ 14, 21, 28, 35, 42.$$

The smallest sector in either case has a transmission of $\cdot 9^{42} = \cdot 012$ approx., and every power of $\cdot 9$ is obtainable by the two-sector procedure up to the forty-ninth, or roughly, to $\cdot 5$ per cent. The three-sector procedure may be invoked, if desired, to carry the range still lower. This is the grouping to which the disks employed with the apparatus described in the paper correspond roughly, other considerations having rendered it desirable to give special values to some of the disks.

THE TRANSFORMATION OF TRICHROMATIC MIXTURE DATA: ALGEBRAIC METHODS

By J. GUILD, A.R.C.Sc., F.Inst.P., F.R.A.S.

(Optics Department, The National Physical Laboratory.)

MS. received, 11th December, 1924. Read and discussed, 11th December, 1924.

ABSTRACT. The paper describes algebraic methods of transforming colour-mixture equations from one trichromatic system to another.

The procedure suggested differs from that previously described by H. E. Ives, and effects important simplifications in the work involved in its practical application to various problems.

In particular it is shown how measurements made in terms of the arbitrary working primaries of any trichromatic colorimeter can be transformed into any system of standard primaries, or vice versa, without auxiliary measurements other than can be made on the instrument itself used in its normal manner.

Introductory

It is possible to represent any colour by an equation of the form

$$C = \alpha R + \alpha' G + \alpha'' B \qquad \ldots\ldots(1),$$

where α, α', and α'' are relative amounts, measured in suitable units, of three entities which are usually termed "Primaries."

Such primaries may consist of actual colours produced either by isolating monochromatic light of suitable wave-lengths from a spectrum, as in the apparatus of Clerk-Maxwell and Abney, or by the use of coloured glasses or stained gelatine filters, as in the colorimeters of F. E. Ives and others. The only condition which it is necessary that three primaries should fulfil is that the sensation of white can be matched by mixing them in suitable proportions. An infinite number of sets of primaries exist which fulfil this condition*. A characteristic common to all trichromatic systems of which the primaries are actual colours is that one or other of the coefficients in equation (1) may have negative values when C is a colour of high saturation.

It is also possible to assume an infinite number of hypothetical sets of primaries, not observable as separate sensations by a normal eye, which can be made the bases of trichromatic systems in terms of which colours may be expressed as in equation (1). Such primaries lie outside the field of separately perceivable sensations and so cannot be embodied in colour matching instruments. They have nevertheless utility for colour specification, inasmuch as it is possible to deduce primaries in terms of which all colours may be expressed without negative coefficients.

* This condition is not really *necessary*. It is, however, *very convenient* in that it renders possible the simple and practically useful choice of units universally employed for equations such as (1).

The three "Fundamental Sensations" of the Young-Helmholtz theory, as derived by Koenig and H. E. Ives from colour mixing data, are an example of such primaries. Whether these "fundamental sensations" have any real existence in the processes of vision is immaterial to the present discussion, in which we need only regard them as forming one of an infinite number of possible co-ordinate systems in which the experimental facts of colour mixture may be expressed, without regard to any special significance which may attach to them from the point of view of visual theory.

As regards the units in which quantities of the primaries are measured, it is convenient to adopt the convention that equal quantities of the three match white.

Further, except where circumstances require otherwise, no quantitative significance is attached to the *amount* of the colour C which equation (1) represents: it is regarded as defining the quality of the colour irrespective of its luminosity and the actual values of α, α', and α'' may be anything at all so long as they bear the correct ratios to each other. Such an equation in its general form is therefore simply a specification of colour quality. When it is necessary to establish a quantitative relationship between two colours specified by two such equations, suitable restrictions have to be imposed on the actual as well as the relative values of the various coefficients.

The great practical importance of trichromatic systems of colour specification lies in the fact that the correlation of different methods of colour measurement, whether trichromatic or not, and calculations of colour from the physical properties of the impulse, can only be made with the help of an intermediate trichromatic system. For instance we cannot calculate directly the hue and purity of a colour from the distribution of energy in the impulse. We can, however, calculate the colour in terms of a set of trichromatic primaries, and from this we can deduce the hue and purity.

The trichromatic system provides, in fact, a means of solving all problems of colour mixture by simple mathematical calculation.

For a comprehensive treatment of the theory underlying such calculations we are indebted to Dr H. E. Ives, to whose researches we owe a large proportion of the important additions to our knowledge of the quantitative aspects of colour vision which have accrued in recent years.

In two papers* Ives develops the theory of a number of important colorimetric relationships and gives methods for applying these to practical problems. His first paper deals with algebraic and his second with graphical methods.

The writer has had occasion to make numerous colorimetric calculations in recent years, and has found it necessary to supplement Ives' theory and to employ somewhat different methods which he has found to be better adapted to the solution of the practical problems arising in colorimetric work.

In view of the importance of the matter in connexion with the standardization

* *Journ. Frank. Inst.* 180 (Dec. 1915) 673; *ibid.* 195 (Jan. 1923) 23. See also, for a brief introduction to the subject, paragraph 9 of an article on the Eye by the present writer in Glazebrook's *Dictionary of Applied Physics*, vol. IV.

of colour measurements and specifications, it seems desirable to call attention to the methods adopted by the writer where these differ appreciably from those described by Ives. The present paper will deal with algebraic transformations only, the discussion of geometrical methods being reserved for another communication.

Transference from One Set of Primaries to Another

It is frequently required to transform results from one set of trichromatic primaries to another. For example, it may be desired to compare readings taken on different trichromatic colorimeters, or it may be desired to transform the results obtained with the arbitrary primaries of such an instrument to a standard system, or vice versa. The problem always reduces to this: given the specification of a colour in the form

$$C = \alpha R_1 + \alpha' G_1 + \alpha'' B_1 \qquad \text{.....(2),}$$

which expresses it in terms of one set of primaries, to which we shall refer as the old primaries, it is required to find the coefficients in the equation

$$C = \beta R_2 + \beta' G_2 + \beta'' B_2 \qquad \text{.....(3),}$$

where R_2, G_2, and B_2 are the primaries of the new system.

To make this transformation it is necessary to know the coefficients which express *unit quantities* of the old primaries in terms of the new; thus

$$\left.\begin{aligned} R_1 &= aR_2 + a'G_2 + a''B_2 \\ G_1 &= bR_2 + b'G_2 + b''B_2 \\ B_1 &= cR_2 + c'G_2 + c''B_2 \end{aligned}\right\} \qquad \text{.....(4).}$$

The units in each system are so chosen that equal quantities of the primaries make white. For convenience, also let the units in the two systems be so related that unit quantities of each set make the *same amount* of white. Then

$$R_1 + G_1 + B_1 = R_2 + G_2 + B_2,$$

from which it follows that, if both sides of equations (4) are expressed in the correct units,

$$a + b + c = a' + b' + c' = a'' + b'' + c'' \qquad \text{.....(5).}$$

Assuming, therefore, that we have equations (4) with the coefficients in the three equations so related as to conform to (5), we substitute the new-system values of R_1, G_1, and B_1 in equation (2), thus:

$$\begin{aligned} C = {} & \alpha\,(aR_2 + a'G_2 + a''B_2) \\ & + \alpha'\,(bR_2 + b'G_2 + b''B_2) \\ & + \alpha''\,(cR_2 + c'G_2 + c''B_2) \\ = {} & (\alpha a + \alpha' b + \alpha'' c)\,R_2 + (\alpha a' + \alpha' b' + \alpha'' c')\,G_2 + (\alpha a'' + \alpha' b'' + \alpha'' c'')\,B_2, \end{aligned}$$

whence by equation (3)

$$\left.\begin{aligned} \beta &= \alpha a + \alpha' b + \alpha'' c \\ \beta' &= \alpha a' + \alpha' b' + \alpha'' c' \\ \beta'' &= \alpha a'' + \alpha' b'' + \alpha'' c'' \end{aligned}\right\} \qquad \text{.....(6).}$$

Starting from equations (4) the process is purely arithmetical. The real problem

of transformation lies in obtaining these equations. The nature of this problem depends on the information which is initially available.

The simplest case arises when R_1, G_1, and B_1 are spectral primaries (monochromatic light of given wave-length) and when we know the mixture curves of the spectrum* for R_2, G_2, and B_2. We can write down from these curves colour quality equations for R_1, G_1, and B_1 in terms of R_2, G_2, and B_2. In general the quantities represented by these equations will not be in the proportions which make white. We must write them in the form

$$\left.\begin{aligned} R_1 &= x\,(eR_2 + e'G_2 + e''B_2) \\ G_1 &= y\,(fR_2 + f'G_2 + f''B_2) \\ B_1 &= z\,(gR_2 + g'G_2 + g''B_2) \end{aligned}\right\} \qquad \text{.....(7),}$$

where e, f, g, etc., are the values obtained from the mixture curves and x, y, and z are unknown numerical factors such that each equation represents unit quantity.

In order that $R_1 + G_1 + B_1 = R_2 + G_2 + B_2$ we must have

$$\left.\begin{aligned} xe + yf + zg &= 1 \\ xe' + yf' + zg' &= 1 \\ xe'' + yf'' + zg'' &= 1 \end{aligned}\right\} \qquad \text{.....(8).}$$

Solving these equations for x, y, and z, and multiplying the appropriate quantities in equations (7) by the values so derived, we obtain the coefficients required for equations (4).

If we do not know the mixture curves of the spectrum for the new primaries, but if the latter are actually embodied in a colorimeter, we can obtain quality equations, similar to (7), by measuring the colours of the three monochromatic radiations corresponding to R_1, G_1, and B_1 on the instrument.

The same procedure will apply where R_1, G_1, and B_1 are produced by coloured filters, provided these can be made available for measurement on the R_2, G_2, B_2 instrument.

For these cases no simplification of the above procedure, which is that given by Ives, is feasible, the experimental data required being the minimum possible under the circumstances postulated.

Difficulty arises, however, when it is not possible to obtain the quality equations of the old primaries in terms of the new directly from the mixture curves of the latter, or, alternatively, by direct measurement on a colorimeter embodying the latter.

In such cases, in order to deduce the coefficients of equations (7) from experimental data, it is necessary

(*a*) to determine spectrophotometrically the wave-length transmission curves of each of the filters constituting the old primaries,

(*b*) to determine the energy distribution in the spectrum of the illuminant used behind them, or, alternatively, to employ a lamp under standardized conditions for which the energy distribution may be assumed,

* i.e. the curves showing the relative amounts of R_2, G_2, and B_2 required to match monochromatic light of different wave-lengths throughout the spectrum.

(*c*) to investigate any instrumental peculiarity from which it may happen that the actual stimulus reaching the eye has not exactly the composition deduced from the energy structure of the primaries and the amounts of these indicated by the settings of the instrument.

In addition to the above information on the properties of the old system it is necessary to know

(*d*) the mixture curves of the spectrum for the new primaries.

In a well-equipped physical laboratory the measurements involved under (*a*) and (*b*) are of a straightforward character, but require the expenditure of considerable time and care if the requisite accuracy is to be attained with certainty. The third factor (*c*) in the problem is not mentioned by Ives, but may be of considerable importance in some types of instrument. It introduces an element of uncertainty which is extremely difficult to eliminate.

All the above information concerning the old primaries is unnecessary for the normal use of the instrument to which they belong. It has to be obtained purely for the purposes of the transformation.

Further, in the case of the new primaries, mixture curves of the spectrum may not necessarily be already available, nor may they be required for the purposes to which the new primaries are to be put. In such a case, therefore, the determination of the mixture curves has to be made specially for the purpose of transformation of data. This is a particularly difficult determination, replete with traps for the experimenter who has not wide experience of such work.

In fact, not only do the processes involved in (*a*), (*b*), (*c*), and (*d*) require considerable labour and time in the best of circumstances, but there is not one of them within the scope of, say, an industrial worker in a laboratory of modest dimensions in which the colorimeter may be the principal item of equipment.

The procedure adopted by the present writer eliminates all the difficulties just outlined, and enables trichromatic data on any set of working primaries to be transferred to any other system of real or hypothetical primaries, and vice versa, without any knowledge of quantities other than those which enter directly into the particular problem, or can be measured directly in terms of the working primaries.

This simplification is effected by starting the transformation not from equations (7), which give the colour of the *old* primaries in terms of the *new*, but from equations giving the colour of the *new* primaries in terms of the *old*. This transformation, which is not treated by Ives, is as follows. Suppose we have undetermined quantities of the new primaries expressed on the old system by the equations

$$\left.\begin{aligned} \lambda R_2 &= lR_1 + l'G_1 + l''B_1 \\ \mu G_2 &= mR_1 + m'G_1 + m''B_1 \\ \nu B_2 &= nR_1 + n'G_1 + n''B_1 \end{aligned}\right\} \qquad \text{.....(9),}$$

in which λ, μ, and ν are numerical factors introduced so that the quantity scales of the three equations should correspond.

Solving these for R_1, G_1, and B_1 we obtain

$$\left.\begin{aligned} R_1 &= \frac{p}{\mu\nu D}R_2 - \frac{p'}{\lambda\nu D}G_2 + \frac{p''}{\lambda\mu D}B_2 \\ G_1 &= -\frac{q}{\mu\nu D}R_2 + \frac{q'}{\lambda\nu D}G_2 - \frac{q''}{\lambda\mu D}B_2 \\ B_1 &= \frac{r}{\mu\nu D}R_2 - \frac{r'}{\lambda\nu D}G_2 + \frac{r''}{\lambda\mu D}B_2 \end{aligned}\right\} \quad \text{.....(10),}$$

where p, p', p''; q, q', q''; r, r', r'' are the values of $(m'n'' - n'm'')$, $(l'n'' - n'l'')$, $(l'm'' - m'l'')$; $(mn'' - nm'')$, $(ln'' - nl'')$, $(lm'' - ml'')$; $(mn' - nm')$, $(ln' - nl')$, $(lm' - ml')$, and D is a common denominator which need not be evaluated.

To have the correct units in both systems, so that $R_1 + G_1 + B_1 = R_2 + G_2 + B_2$, we must choose the values of λ, μ, and ν so that the sum of the coefficients of each of the new primaries is unity.

Thus
$$\begin{aligned} \mu\nu D &= p - q + r \\ \lambda\nu D &= -(p' - q' + r') \\ \lambda\mu D &= p'' - q'' + r'' \end{aligned}$$

and equations (10) become

$$\left.\begin{aligned} R_1 &= \left(\frac{p}{p-q+r}\right)R_2 + \left(\frac{p'}{p'-q'+r'}\right)G_2 + \left(\frac{p''}{p''-q''+r''}\right)B_2 \\ G_1 &= -\left(\frac{q}{p-q+r}\right)R_2 - \left(\frac{q'}{p'-q'+r'}\right)G_2 - \left(\frac{q''}{p''-q''+r''}\right)B_2 \\ B_1 &= \left(\frac{r}{p-q+r}\right)R_2 + \left(\frac{r'}{p'-q'+r'}\right)G_2 + \left(\frac{r''}{p''-q''+r''}\right)B_2 \end{aligned}\right\} \quad \text{...(11).}$$

These equations are of the form of equations (4) and fulfil equations (5). They are therefore the equations required for the arithmetical conversion of data from the R_1, G_1, B_1 system to the R_2, G_2, B_2 system.

Practical Applications

The most important practical problem in connexion with standardization of colour measurements is the conversion of readings obtained with the arbitrary primaries of a trichromatic colorimeter into some standard reference system. Such a reference system may consist of three monochromatic primaries of specified wave-length, or may consist of non-spectral primaries such as the Koenig-Ives fundamental sensations.

In the first case, it is merely necessary to make measurements, on the working colorimeter, of the monochromatic radiations which constitute the reference primaries. The readings of the instrument give us l, l', l''; m, m', m''; and n, n', n'', of equations (9) directly.

It will be noted that it is not necessary to know the mixture curves of the spectrum for the reference primaries, but only the colour quality of these primaries themselves as measured on the instrument containing the working primaries.

This is extremely important because it enables us to *determine* spectral mixture curves for any selected set of spectral primaries by measurements made on any convenient set of working primaries.

For this last purpose it may not be obvious where any advantage is gained by this procedure as compared with a direct determination of the reference primary mixture curves with a colorimeter employing the reference primaries themselves.

The advantage is entirely of a practical character. It is very difficult to design a satisfactory colorimeter in which spectral primaries are employed. To discuss the reasons for this would unduly extend this paper. Suffice it to say that had the difficulties not been exceedingly great there would probably have been as numerous determinations of the colour mixture curves of some selected set of monochromatic primaries as there have been of the visibility function in recent years, instead of which, apart from the few observations of Koenig, which appear to be the only reasonably accurate determinations—and even these are seriously in question—there is no reference system of trichromatic mixture curves available.

In all really practicable trichromatic colorimeters the primaries are produced by coloured filters in conjunction with a source having a continuous spectrum. We may determine the mixture curves of the spectrum for the arbitrary primaries of such an instrument and, by using the method of transformation here described, convert them, without any auxiliary experimental work, to any set of spectral primaries we choose.

The conversion of data from the working primaries to the non-spectral reference system of the Koenig-Ives fundamental sensations is equally simple in practice, though the derivation of the final transformation equations must be done in two steps.

We cannot, of course, take readings of the sensation primaries directly on the colorimeter as in the case just considered, but this is not necessary. *It is only necessary to make measurements on three different monochromatic radiations which could themselves serve as the primaries of a trichromatic system.*

Denote the working primaries, as before, by R_1, G_1, and B_1, the three monochromatic radiations by R_2, G_2, and B_2, and the sensation primaries by R_3, G_3, and B_3.

The measurements on R_2, G_2, and B_2 give us equations (9) expressing the intermediate spectral primaries in terms of the working primaries, which lead to equations (11), expressing the working primaries in terms of the spectral primaries. Let these, when the coefficients are evaluated, be

$$\left.\begin{aligned} R_1 &= sR_2 + s'G_2 + s''B_2 \\ G_1 &= tR_2 + t'G_2 + t''B_2 \\ B_1 &= uR_2 + u'G_2 + u''B_2 \end{aligned}\right\} \qquad \text{.....(12).}$$

From the sensation mixture curves of the spectrum we can write down the quality equations expressing R_2, G_2, and B_2 in terms of R_3, G_3, and B_3. These

are equivalent to (7), which lead, in turn, to equations equivalent to (4), suitable for converting data from the R_2, G_2, B_2 system to the R_3, G_3, B_3 system.

Let these, after evaluation of the coefficients, be

$$\left.\begin{aligned} R_2 &= vR_3 + v'G_3 + v''B_3 \\ G_2 &= wR_3 + w'G_3 + w''B_3 \\ B_2 &= xR_3 + x'G_3 + x''B_3 \end{aligned}\right\} \qquad \text{.....(13).}$$

Substituting these expressions in (12), we obtain

$$\left.\begin{aligned} R_1 &= (sv + s'w + s''x)\,R_3 + (sv' + s'w' + s''x')\,G_3 + (sv'' + s'w'' + s''x'')\,B_3 \\ G_1 &= (tv + t'w + t''x)\,R_3 + (tv' + t'w' + t''x')\,G_3 + (tv'' + t'w'' + t''x'')\,B_3 \\ B_1 &= (uv + u'w + u''x)\,R_3 + (uv' + u'w' + u''x')\,G_3 + (uv'' + u'w'' + u''x'')\,B_3 \end{aligned}\right\} \text{(14).}$$

Equations (14) enable us to convert data from the working primaries to the sensation primaries in one step. The introduction of the intermediate system of spectral primaries is merely a device which enables us to calculate the coefficients of transformation from measurements made on three monochromatic radiations instead of on the ultimate primaries themselves.

The last case is a particular example of a general proposition, viz., that if the spectral mixture curves of the system into which we wish to transfer are known, we may derive the necessary equations of transformation from measurements on three monochromatic radiations which need not be the reference primaries themselves. At present, as already mentioned, the fundamental sensation mixture curves constitute the only well-established system available, but this state of affairs cannot continue, because a proper co-ordination of colorimetric work is impossible until data are obtained which represent the average eye with the same certainty as the existing visibility data. Such data, when obtained, will probably be expressed in terms of spectral primaries of some agreed wave-lengths. Normally the procedure followed in obtaining the transformation equations required to convert the readings of a colorimeter to this reference system will be to make measurements of the reference primaries themselves. Practical considerations may sometimes, however, make it easier to obtain readings for wave-lengths other than those. This will largely depend on the equipment available to the experimenter. A spectroscope to separate the required wave-lengths may not be at hand; but in such a case the red line of hydrogen, and the green and blue lines of mercury, as obtained from vacuum lamps, in conjunction with suitable Wratten filters could be used. In fact, except in laboratories suitably equipped for standardization research, it will usually be safer to obtain standard monochromatic colours by such means than by spectroscopic separation from a continuous spectrum, owing to the difficulties of avoiding error in the latter method due to stray light, slit width corrections, etc.

As a worked example of the use of the transformation which is the basis of the present paper, let us calculate the equations for converting the Koenig-Ives sensation curves to a system of spectral primaries, say $R_2 = \cdot 656\mu$; $G_2 = \cdot 520\mu$; and $B_2 = \cdot 436\mu$. In this case the sensation primaries are the old set and the spectral primaries the new. These particular primaries are selected because they are one of a series of

sets for which the author has made the calculation, and the results are available without further work.

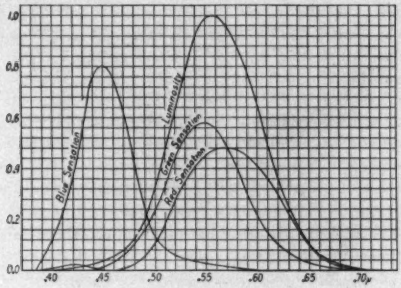


Fig. 1

Table I

λ μ	R_2	G_2	B_2	λ μ	R_2	G_2	B_2
·38	0·0		0·0	·55	·440	·576	·0216
·39	·0029		·0485	·56	·466	·555	·0168
·40	·0073		·127	·57	·472	·496	·0138
·41	·0118		·230	·58	·464	·396	·0105
·42	·0144		·365	·59	·440	·288	·0051
·43	·0117	0·0	·588	·60	·399	·199	·0024
·44	·0065	·0039	·763	·61	·349	·133	·0009
·45	0·0	·0147	·803	·62	·288	·0921	·0005
·46	·0009	·0319	·756	·63	·212	·0551	·0002
·47	·0090	·0598	·630	·64	·150	·0134	0·0
·48	·0203	·100	·421	·65	·0934	·0180	
·49	·0575	·154	·217	·66	·0561	·009	
·50	·117	·231	·117	·67	·0380	·0052	
·51	·192	·334	·0778	·68	·0140	·0022	
·52	·268	·442	·0521	·69	·0090	·0013	
·53	·335	·518	·0361	·70	·0048	·0007	
·54	·396	·564	·0282				

In Fig. 1, which is taken from Ives' second paper, are the three fundamental sensation curves of Koenig as modified by Ives. The luminosity curve of the white light spectrum is also given in the diagram, but we are not concerned with this. Table I gives the numerical data from which the mixture curves are plotted. We find from the table, interpolating where necessary, that the new primaries are given in terms of the sensation primaries, which we now denote by R_1, G_1, and B_1, by the equations

$$\lambda R_2 = \cdot 070 R_1 + \cdot 0126_5 G_1 + 0\cdot 000 B_1$$
$$\mu G_2 = \cdot 268 R_1 + \cdot 442 G_1 + \cdot 052 B_1$$
$$\nu B_2 = \cdot 0088 R_1 + \cdot 0011 G_1 + \cdot 710 B_1$$

In the notation of equations (9), (10), and (11),

$$\begin{aligned}
p &= \cdot 442 \times \cdot 710 - \cdot 0011 \times \cdot 052 &&= \cdot 3138\\
p' &= \cdot 0126_5 \times \cdot 710 - \cdot 0011 \times 0 &&= \cdot 0090\\
p'' &= \cdot 0126_5 \times \cdot 0521 - \cdot 442 \times 0 &&= \cdot 0007\\
q &= \cdot 268 \times \cdot 710 - \cdot 0088 \times \cdot 052 &&= \cdot 1898\\
q' &= \cdot 070 \times \cdot 710 - \cdot 0088 \times 0 &&= \cdot 0497\\
q'' &= \cdot 070 \times \cdot 0521 - \cdot 268 \times 0 &&= \cdot 0036\\
r &= \cdot 268 \times \cdot 0011 - \cdot 0088 \times 442 &&= -\cdot 0036\\
r' &= \cdot 070 \times \cdot 0011 - \cdot 0088 \times \cdot 0126_5 &&= \cdot 0000\\
r'' &= \cdot 070 \times \cdot 442 - \cdot 268 \times \cdot 0126_5 &&= \cdot 0275
\end{aligned}$$

$$\begin{aligned}
p - q + r &= \cdot 1204\\
p' - q' + r' &= -\cdot 0407\\
p'' - q'' + r'' &= \cdot 0246
\end{aligned}$$

Evaluating the coefficients of equations (11) from the above values, we find as our equations of transformation

$$\left.\begin{aligned}
R_1 &= 2\cdot 606R_2 - \cdot 221G_2 + \cdot 028B_2\\
G_1 &= -1\cdot 576R_2 + 1\cdot 221G_2 - \cdot 146B_2\\
B_1 &= -0\cdot 030R_2 + 0\cdot 000G_2 + 1\cdot 118B_2
\end{aligned}\right\} \quad \ldots\ldots(15).$$

Applying these equations to the sensation values as given in Table I we obtain the mixture curves for the given spectral primaries. These are shown in Fig. 2.

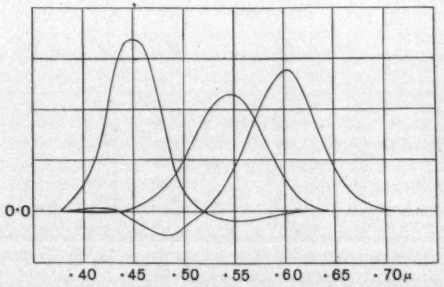


Fig. 2

It will be noted that in the process of transforming the mixture curves of one set of primaries into those of another set by the method of this paper it is unnecessary to introduce the luminosity curve in order to get the proper proportions between the ordinates. The application of the equations of transformation to the quantities of the old primaries *as they are obtained from the old mixture curves* gives the quantities of the new primaries on the correct magnitude scale for plotting directly as ordinates of the new mixture curves.

DISCUSSION

Dr L. C. Martin: Mr Guild's paper is a very useful one. The tendency in all exact measurement is to rely more and more on well-defined arbitrary standards. His suggestion is, as I understand it, that a set of measurements made by a trichromatic colorimeter can be referred to such standards through measurements made with the colorimeter on the standards themselves. I think the difficulty would be in deciding on what standards to adopt. The suggestion of standard spectrum lines isolated with suitable filters seems difficult to me because no "additive" colorimeter will give accurate matches with pure monochromatic light. It is necessary to be able to put one of the three components into the opposite colorimeter field in order to be able to secure the necessary negative coefficient in the equation. It would certainly lead to complication in the colorimeter and I am not aware that it has been successfully done. The alternative of lowering the purity of the monochromatic stimulus by dilution with white light would apparently lead to other difficulties. Has Mr Guild been able to overcome these difficulties in practice? If so, it will add greatly to the interest of the theory.

If standards are required, it may be possible to prepare filters of known properties, but the use of standard lines sounds very attractive if the experimental complications are not too great.

Dr Herbert E. Ives (communicated): The problem of transforming measurements of colour made by any type of colorimeter (or spectrophotometer) into equivalent readings on some other type of colorimeter is one which first attracted my attention in 1908 when I had occasion to make some measurements of illuminants on a three-colour mixture instrument employing red, green, and blue colour filters to produce its primaries. I found, at that time, that the necessary information for effecting such transformations was to be found in various publications by Koenig and Abney, but that it had never been put in shape for handling the specific problems met in colour measurement. The interest in the subject aroused at that time has led me, from time to time since then, to work out and publish the solutions of certain transformation problems, using for some of these aglebraic and for others graphical methods. I believe that I have by one method or another covered the chief practical problems and have pretty well indicated the general theory which may be followed in any problems of this sort.

The fact that the work, to which I referred, has been done from time to time with reference to certain special problems which have been handled by methods which seemed most appropriate to each has resulted in considerable incompleteness and lack of balance of treatment. For instance, some of the problems which have been handled by graphical means, such as the production of spectrum mixture curves for any desired primaries, could, it is obvious, be worked out also by algebraic methods. In general my own preference in working has been to use, wherever possible, graphical schemes. The algebraic expressions for the more

complicated transformations become, as Mr Guild's paper shows, rather lengthy and complicated.

I have practically nothing in the way of either constructive or destructive criticism of Mr Guild's interesting paper, which I have read with great pleasure. Mr Guild is carrying through with great success the completion of the algebraic methods. I shall be interested to learn from his promised paper on graphical methods whether he does not find these on the whole easier and quicker to work with.

The method proposed by Mr Guild for obtaining the coefficients for transformation by measurements on an intermediate system of spectral primaries is ingenious and has elements, which he describes, of great practical utility. It may be pointed out in this connexion that measurements on monochromatic radiations require that the three-colour mixture instrument be provided with means for mixing white with the monochromatic radiation under measurement, since the trichromatic mixtures will always be under-saturated. This emphasizes the necessity of having available some laboratory source of standard white light. It is possible that the most satisfactory means for obtaining this will be the rotatory polarization method advocated by Mr Priest.

In this country, the trend of opinion in colour nomenclature and specification has been toward transforming colour measurements into terms of spectral hue, saturation, and luminosity. Measurements on this latter system are much more difficult to make than by a trichromatic system, in which every measurement gives an exact match in the field of the instrument. There is, I think, considerable force to the argument that the description of a colour in terms of three primaries will never convey as easily grasped information to the person interested in colour as may be conveyed by a description in which the dominant hue is described. It is because of this trend of opinion that we have here been devoting rather more attention to the transformation of colour measurements and spectrophotometric measurements into terms of spectral hue, saturation, and luminosity.

Mr Guild: In reply to Dr Martin, it is necessary that any trichromatic colorimeter, unless intended for very limited uses, should be provided with means of desaturating the colour under test, where this is required in order to enable an exact match to be made in the field of the colorimeter. Apart altogether from measurements on monochromatic light many filters and pigmented materials have colours more saturated than can be matched with any generally useful set of primaries. The suggested use of monochromatic standard primaries for reference purposes does not therefore involve any fresh problem in instrument design.

In the trichromatic colorimeter designed by me some years ago, which, though not yet described in the ordinary way, was on view at Wembley Exhibition last year, it is perfectly easy to add to the colour under test any one of the primaries, white, or any other colour producible by filters. It should be borne in mind in this connexion that the constituent to be added to the colour under test may be any colour whatever, provided a mixture is produced which lies inside the colour triangle of the primaries. That it should be one of the primaries (namely the one which will appear with a negative coefficient in the resultant expression) is convenient

from the point of view of its easy subsequent evaluation, but in some cases it may be useful to add simply the whitish light from the lamp employed as an illuminant for the primaries. The constitution of this light is immaterial, as it is evaluated subsequently in terms of the instrument primaries and subtracted from the measurements.

I am indebted to Dr Ives for the trouble he has taken in communicating his views on this paper. I trust that, despite the time interval involved in such an interchange of views, the Society may be favoured in the future by many contributions to its discussions from those American scientists who, like Dr Ives, are responsible for important fundamental developments in subjects which are of interest to us.

I am in entire agreement with Dr Ives in regard to a general personal preference for graphical methods in the solution of problems of colour mixture. Where one calculation—or at most a few calculations—of a given type have to be made the graphical methods are usually more expeditious. Not only so, they give a pictorial representation of the phenomena which renders it almost impossible to make a mistake, whereas an arithmetical error in a purely algebraic calculation may pass unsuspected. In a subsequent paper I shall describe graphical methods of performing these same transformations, which, for any individual transformation, will be found much quicker in practice than the methods of the present paper.

The matter is different, however, where it is necessary to make a large number of similar calculations, involving the same two trichromatic systems. In such a case the work involved in the initial computation of the equations of transformation serves for all subsequent transformations between these systems. Any individual transformation then merely involves the multiplication and addition of numerical coefficients, a process which is, of course, much more quickly carried out than a graphical operation.

Incidentally, the equations of transformation obtained algebraically in the present paper may, if desired, be obtained graphically. There are, in fact, two distinct general methods of transforming data between two trichromatic systems. In one method we may operate directly on each colour to be transformed, the same process, or the greater part of it, having to be performed for each transformation. This is generally the preferable method where we are only interested in a few transformations. In the second method we first obtain the general transformation equations which connect the two systems, the subsequent work for any individual transformation being merely numerical. This method is preferable where numerous transformations between two systems are involved, as in calculating mixture curves of the spectrum, or in transferring the results of measurements on a working colorimeter to a standard system. The required equations of transformation for this method may be obtained algebraically, as in the present paper, or graphically, as will be explained in the next. It is largely a question of individual taste which mode of obtaining them is employed. Personally I like to use both, as a check on numerical work.

It would be outside the scope of the present paper to discuss the relative merits of the trichromatic or monochromatic systems *as bases of specification and*

nomenclature. As practical systems of *measurement*, in whatever form the results have finally to be expressed, both systems are important, as, indeed, are various others which have been made the bases of more or less empirical systems of measurement. The outstanding importance of the trichromatic system is that it provides us with a means of calculating colour from a spectrophotometric analysis of the stimulus, and in this way provides a means of transforming results from any rational system of colour measurement into any other. Thus, irrespective of which system may ultimately be found best in which to express colour specifications, an intermediate trichromatic system is essential in order to convert to such standard system results obtained with instruments based on other systems. Further, the trichromatic system is the only one in which calculations of colour mixture can be made. Suppose we have two colours specified in terms of hue, saturation, and luminosity factor. We cannot calculate, within the terms of this system, the colour due to mixing these in specified proportions. We have first to transform the data into a trichromatic system, make the mixture calculation in terms of this system, and then transform the result back into hue, saturation, and luminosity. Thus a well-established trichromatic system is a *sine qua non* of progress in colorimetric work, and it was primarily to facilitate the acquisition of standard data for the spectrum, from which all other colours are derived, that the present paper was written.

This point is not, needless to say, in reply to Dr Ives, but for the information of those who, through unfamiliarity with Dr Ives' work, might gather from the last paragraph of his communication that the adoption of the monochromatic system of specification would render trichromatic systems unimportant.

EXHIBIT OF A SIMPLE MICROPHOTOMETER

By L. C. MARTIN, D.I.C., A.R.C.S., D.Sc.

(Lecturer in the Optical Engineering Department,
Imperial College of Science and Technology.)

Exhibited, 11*th December*, 1924.

In connexion with an experimental confirmation* of certain calculations† regarding the distribution of light in star images exhibiting small amounts of coma, it was desired to compare the opacities of extremely small areas on a photographic plate and for this purpose a special microphotometer was constructed from such apparatus as was available in the laboratory, and a few easily constructed accessories. The attention of the writer has, however, been drawn to three French papers‡ in which apparatus embodying substantially the same principle is described, and also to microphotometers of the registering type§ in which similar optical arrangements are used. Nevertheless, inasmuch as the automatically registering instruments are complicated and costly, and the writer's instrument contains nothing expensive beyond an ordinary microscope (probably already available in most laboratories), it has been thought worth while to give a short description. The instruments of the Hartmann type (which are well known) have the defect that they show the grain of the photographic plate in the photometric field, and this is one of the factors which have prejudiced the growth of this side of photographic photometry. Nevertheless, with the instrument described below the opacities of parts of the images, etc. may be measured with ease and rapidity by visual observation because the parts of the photometric field are perfectly uniform.

A general plan of the apparatus is given in the figure. The source of light P, a "Pointolite" lamp, is enclosed in a box where it illuminates two screens of opal glass O_1 and O_2. The light diffused from these screens illuminates two apertures A_1 and A_2 respectively (in the latter case with the aid of the mirror M). Immediately outside A_1 is a photometric wedge W, by means of which the intensity of the light from A_1 may be varied in a known manner, the wedge having been calibrated for this purpose. The lens P_1, held in the special fitting screwed into the body tube of a microscope, now projects an image of the aperture A_1, with the aid of the silvered reflecting surface in the small Lummer-Brodhun cube L, into the plane of the diaphragm D pierced in its centre by a small hole about 1 mm. in diameter.

An eye looking through the aperture in D now sees the photometric field formed by the Lummer-Brodhun cube with its outer part brightly illuminated by the light from A_1. We neglect at present the function of the lens F.

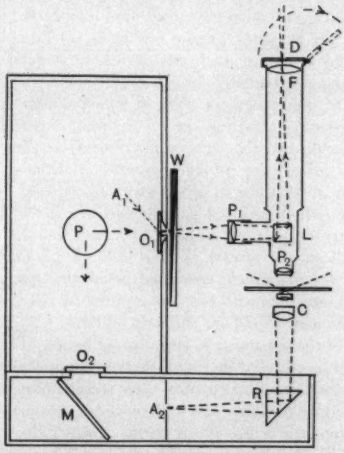
* *Trans. Opt. Soc.* 24 (1922–23) 1.

† *Monthly Notices, R.A.S.* 82 (1921–22) 317.

‡ Buisson and Fabry, *Compt. Rend.* 156 (1913) 389; H. Chretien, *Bull. de la Soc. Astr. de France* (Feb. 1913) p. 59; Baillaud, *ibid.* (Dec. 1913) p. 527 and (Jan. 1914) p. 27.

§ Moll, *Proc. Phys. Soc.* 33 (1921) 207; Goos, *Z. f. Instrk.* 41 (1921) 313.

The light diverging from A_2 proceeds to the right-angled prism R, whence it is reflected to the achromatic condenser C of the microscope; the condenser thus forms in the film of the photographic plate a diminished image of the bright aperture A_2. The image of the part of the plate thus illuminated is projected by the microscope objective P_2 into the plane of the diaphragm D, where an eye looking through the small aperture now sees the central part of the field illuminated by light which has passed through the plate. In effect, the part of the plate to be considered is that which lies inside the bounds of the image of the aperture D which may be considered to be formed by the microscope objective P_2. A convenient focal length for the latter is about $\frac{2}{3}$ inch. Thus, if the distance of the diaphragm from the back principal focus of the lens is, say, 8 inches, the part of



the plate concerned would be a circle $\frac{1}{12}$ mm. in diameter if D is 1 mm. It is not often that such a small area needs to be dealt with and the diameter of the aperture at D may be suitably enlarged if required. The necessary condition for satisfactory illumination of the field is that the images of the apertures A_1 and A_2 shall completely cover the aperture in D. If the images only partially cover the aperture, the slightest unsteadiness of the apparatus is likely to cause a variation in the relative brightness of the two halves of the field; and, further, diffraction effects are troublesome. We see, therefore, that the image must completely overlap the aperture on all sides or completely pass through, if the requisite constancy of the field brightness is to be maintained. This important provision is one of very general application in photometric work.

Baillaud's apparatus*, although using a similar principle, does not employ small apertures such as A_1 and A_2; but this is a very serious drawback owing to the effects of stray light. Suppose, for example, that it is desired to investigate the density of part of an extremely small star image. If this is duly brought to the conjugate focus of the aperture in D it is true that, of the direct light, only that passing through the image can reach the eye. Nevertheless, if the surrounding parts of the plate are brightly illuminated, the intensity of the stray light in the field will be very considerable. This is the great advantage of using the aperture A_2, for the portion of the plate illuminated can be reduced to the region immediately surrounding the exact part under examination. The use of a good achromatic condenser of high numerical aperture also confers another advantage, namely, that the cone of light illuminating the plate has a large angle. Hence the condition is fulfilled that for a proper measurement of "plate density" the illumination of the film must be diffuse. Naturally in making a series of comparative measurements it is important to keep to one type of illumination.

There is, of course, no reason why the shape of the apertures D and A_2 should not be modified to suit particular cases. Thus in measuring the densities of the images of spectrum lines both apertures may be made linear, and so on. The light perceived by the eye is then of an amount proportional to the integrated effect of the whole effective aperture.

The function of the field lens F is two-fold. It is made of a power sufficiently great to bring the photometric field into sharp focus to an eye at rest and thus serves to facilitate observation. Secondly, the diaphragm D is hinged so that it may be swung aside and the lens exposed. If now the diaphragm containing the aperture A_2 be removed, a large part of the plate will be illuminated and its image formed in the plane of the lens F. By drawing back the head or by using a supplementary lens the image of a considerable part of the plate may thus be examined. It is advisable to stop the light from the wedge during this operation. It is possible at once to see which part of the plate is being used for the examination of the density by marking a small ring on the surface of F immediately corresponding to the position of the aperture in D.

The plate C is carried upon the mechanical stage of the microscope. There is usually no difficulty in mounting a quarter-plate, but larger ones would have to be cut. The principles of the present construction would naturally lend themselves to the making of a larger *ad hoc* instrument if such were required.

In its first and somewhat cruder form this instrument has been found most convenient for determining the densities of small parts of photographic star images, and it has also been used with encouraging results for the determination of the densities of small regions in photographs of stellar spectra.

* Baillaud, *loc. cit.*

DISCUSSION

Mr R. Kingslake: Can Dr Martin give any idea of the method by which the optical density of the image on the photographic plate can be measured absolutely?

Dr Martin: The apparatus would need to be calibrated with the aid of a plate or filter of known absolute density. It would then be easy to adjust the pointer attached to the wedge *W* so that it would give direct absolute readings.

EXHIBIT OF AERO-LENS TESTING BENCH

By B. K. JOHNSON

(Optical Engineering Department, Imperial College of Science and Technology.)

Exhibited, 13th November, 1924.

Owing to the Department's possession of some large aircraft lenses and to the fact that suitably large apparatus* for testing these was not available, it was decided to design and construct this apparatus in the department. Those chiefly responsible for the design were Dr L. C. Martin, Mr A. E. Davis, and myself.

It consists essentially of a "nodal slide," with mount for the lens and observing system as shown in Fig. 1. The "bed" *A* of the lens mount moves on a geometric slide *B*, whilst a circular table and V-slide *C* are mounted on top of the main bed in order to provide for the rotary and longitudinal movements of the lens. These movements are actuated, whilst observing, by means of the single control wheel *D* in conjunction with the small clutch handle *E*.

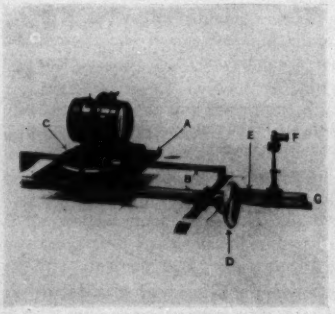


Fig. 1. General view of Aero-Lens Testing Bench.

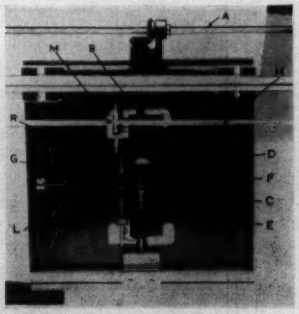


Fig. 2. Showing Underneath View of Lens Carriage.

The observing system consists of an eyepiece fitting *F* attached to an ordinary optical bench stem mounted on a short length of triangular bar *G*. A scale and vernier (reading to ·1 mm.) are fitted to the eyepiece mount, movement being provided by rack and pinion.

The mechanism for operating the lens holder is shown by an underneath view of the bed given in Fig. 2. It is of a somewhat complicated nature, but after much

* Our own Beck bench will not take lenses larger than 6 inches in diameter.

consideration this particular design proved to be the simplest method of attaining the desired result.

The rod *A* (to which is attached the control wheel) drives by means of the bevel wheels the spindle *B*. On this spindle the bevel wheels *D* and *E* can rotate freely, whilst the laterally moving double clutch *C* rotates with it; thus, by engaging the clutch with either *D* or *E*, each of these bevel wheels may be driven independently. *D* and *E*, working in conjunction with their corresponding bevels *F* and *G*, operate the longitudinal and rotary movements of the lens respectively.

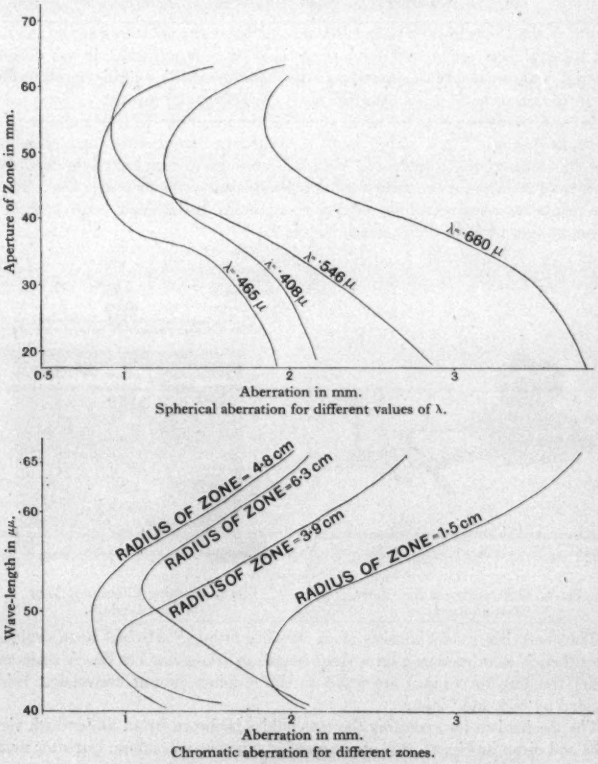


Fig. 3. Steinheil (triplet) Aero-Lens. ($f = 70$ cm. Aperture = $f/5$.)

The bevel wheel *F* is connected directly to a pinion which engages in a rack, thus producing translatory movement. The rod *H* actuates the side to side movement of the clutch by means of an eccentrically mounted cam situated at *M* operating the rod *R* and lever arm *L*.

Fig. 3 shows curves, obtained with the apparatus, giving the chromatic and spherical aberrations of one of the lenses exhibited.

DISCUSSION

Mr J. Guild: Is there no inconvenience in practice due to the absence of any automatic adjustment, as in the Beck lens testing bench, for maintaining the focus of the observing system in the plane of the plate when examining off the axis?

As regards mechanical details what is the advantage of introducing the complication of a clutch mechanism in order to effect both rotation and translation by means of one handle? Two handles have to be operated in any case, as the clutch must be changed over in order to pass from one adjustment to the other, so there is no obvious reason why one handle should not operate the rotation and a second handle the translation without any clutch.

Mr P. F. Everitt: In actual lenses of the size considered the nodal points are not constant and it would appear advisable for Mr Johnson to reconsider his results if these are based on assumed constancy of the nodal points.

Mr Conrad Beck: Mr Everitt's doubt as to whether the back nodal point of a photographic lens is in a fixed position for all angles of obliquity of the incident light arises from experience with lenses which possess distortion. If a lens is free from distortion the back nodal point is in a fixed position as regards the projection of objects at a distance.

Mr Johnson's method of measuring aberrations is not so rapid or convenient as the method employed in the Beck testing bench, but equally reliable if the results obtained are compared with the distance from the nodal point to a flat surface at right angles to the axis at each angle.

Mr Johnson: In this testing bench it has been found from actual practice that there is little or no inconvenience experienced, when examining off the axis, due to the absence of the automatic adjustment mentioned. The rack motion with scale on the eyepiece mount provides sufficient movement for angles up to 15° on each side of the axis (this more than covers the size of plate for which the lens is intended), after which further movement, if desired, is obtained by sliding the optical bench foot along the triangular bar.

As regards the mechanical construction I think it is a matter of choice whether the two handle or single handle device is used; but on consideration it will be found that what at first sight might appear to simplify the design by the introduction of two handles and no clutch action unfortunately only goes to make the construction still

further complicated. Hence the reason for adopting the single handle and clutch device.

I am aware that in lenses, not only of this size but of all sizes, the positions of the nodal points are not constant when the lenses are used at considerable obliquity, but for the small angular range over which these particular lenses are used this fact does not enter into account.

With reference to Mr Beck's remark concerning the lack of rapidity or convenience of measuring aberration as compared with the Beck bench, it must be borne in mind that the bench exhibited was designed with the specific purpose of testing the large aero-lenses belonging to the Department and therefore it could not be expected to be as generally convenient for commercial work as the Beck bench with its many fittings. For the purpose for which the bench was designed, however, it has proved entirely satisfactory.

REVIEWS

Helmholtz's Treatise on Physiological Optics, translated from the third German edition. Edited by Professor JAMES P. C. SOUTHALL. Vol. I. Pp. xxi + 482; 149 Figs., 1 Plate. (The Optical Society of America, 1924.) Price $7 per volume. (The book is not on sale at the booksellers, but may be obtained by sending an order to Prof. F. K. Richtmyer, Cornell University, Ithaca, N.Y.)

Nearly seventy years have elapsed since the first part of Helmholtz' great work on Physiological Optics was published in Germany. From its first appearance it has been regarded, and rightly regarded, as the standard work on this complex subject. That position has not been seriously challenged since, and the later editions prepared by other workers of eminence in this field remain the standard treatises on vision to this day. The absence of any English translation for so long a period reflects the indifference towards optics in its various branches of even the scientific public in this country and America; for this indifference we have paid heavily in the past thirty years, and our continued apathy is likely to cost us dear in the future. As far as we can judge, the lessons of the war have been better appreciated in America than in Britain, and it will certainly not be the fault of Prof. Southall and his collaborators in this work if the American public fails to realize the importance, and at the same time the difficulty and the fascination, of this field of research. We have the opportunity of profiting from their labours, and it is an opportunity which should not be lost. We may say at once, what readers of Prof. Southall's previous books will not need to be told, that the work has been carried out admirably. The text is clear and reads smoothly, betraying neither its alien origin nor the plurality of translators. Obvious errors in the original have been corrected, and the editor has very wisely converted measurements originally given in units now obsolete into their metric equivalents. The Optical Society of America has evidently made every effort to ensure that the volumes should be worthy of their contents. The type is clear (though we prefer the old style of the Society's Journal) and, for an American scientific book, the text is comparatively free from printers' errors, though we must admit that too many remain. The least satisfactory feature is the reproduction of the diagrams, which should be redrawn for any future edition. The common error of describing the unit $m\mu$ as $\mu\mu$ should also be corrected.

The basis of the present translation is the third German edition of 1909–11, including the various modifications and appendixes of Gullstrand, von Kries, and Nagel. These additions deal very fully with the extensions of our knowledge, and also with disputed points, subsequent to the work of Helmholtz himself. The book as a whole is therefore a modern treatise on physiological optics. The volume now under consideration—the first of three—contains Helmholtz' anatomical description of the eye and is followed by that great division of the subject which is classed as the dioptrics of the eye. Here will be found the theoretical foundation on which a multitude of fundamental measurements are based. In actual fact this part is a combination of two treatises of about equal length. One half is due to Helmholtz, the other to Gullstrand. Both deal with their matter in a masterly manner, the former being more concerned with the rudiments, the latter with the higher developments, of the subject. The main divisions concern measurements of the physical constants of the eye both by Helmholtz and by other workers; chapters on the ophthalmoscope and its use, and on accommodation; detailed discussions on the aberrations of the eye; and not least a systematic exposition of the leading properties of

optical systems. The perusal of some of these sections will bring home to the reader a realization of the wide area covered by Helmholtz' own work, and of the extent of our indebtedness to him in showing us order in a field that had appeared almost confusion itself. How sound Helmholtz' work has proved will be appreciated on reading Gullstrand's account of investigations he has himself made with more refined tools than were at Helmholtz' service, to ascertain the truth where the master's conclusions have been assailed. Time after time it appears that not only has Helmholtz' view been decisively confirmed, but where his results were quantitative no certain departures can be made from his numerical results.

A considerable section of this book is occupied with the theory of refracting and reflecting systems as they are required for the explanation of the properties of the eye and for an understanding of the means adopted in making measurements on the living eye. The section illustrates Helmholtz' method well. Obviously the matter must be made clear to varied types of reader, many of whom will have no special aptitude for following a mathematical discussion. The line of reasoning and the conclusions to which it leads are first explained with great care in general terms, and the mathematical discussion follows. The result is that this section forms an introductory treatise on the theory of optical instruments, which could hardly be surpassed—always assuming that a discussion on the ray basis is to be accepted. It is in this portion of the book that the famous Young-Helmholtz law is found.

As would be expected, the work of Gullstrand is more detailed and precise than that of Helmholtz. Gullstrand points out that the theory of the Jena school is not strictly an *optical* theory, however useful it may be in designing instruments which are to approach the ideal but impossible instrument of the collinear theory as closely as possible. In dealing with the eye such conceptions are inapplicable and should be rejected at the outset. The treatment adopted is based on Coddington's equations for meridional and sagittal refraction, though Coddington's name is not mentioned. The derivation of these equations is particularly neat. Owing to the asymmetry of the eye, this is the simplest foundation which can be utilized. The basis here also is purely geometrical. On these relations general equations for imagery are formed and thrown into a particularly pleasing form. In the higher developments of the subject compression becomes essential, and the results obtained are quoted without proof.

It will be gathered from the character of these typical examples that the appearance of this translation is an event of considerable importance, quite apart from historical reasons, owing to the value of the book to a large circle of workers at the present day. Viewed as a modern treatise there is only one respect in which we are inclined to think the discussion unsatisfactory. This lies in the adoption of the ray view of image formation practically throughout the book. For some sections this is undoubtedly a reasonable foundation, but when aberrational defects and out of focus effects are considered it leaves much to be desired. It implies an indefinitely fine image structure, and therefore no rational limits for the appraisement of defects. It is true that Gullstrand is careful to place Helmholtz' famous statement about the defects of the eye as an optical instrument in its proper setting, but a discussion in which these geometrical defects are expressed in terms of errors of phase at the retina would be far more convincing. In fact this aspect of some of the problems is so important that we should be glad to see sections such as "blur circles on the retina" and Gullstrand's "higher order imagery laws" entirely rewritten on this basis. For this we must no doubt wait for a new edition.

It should be noted that the present edition is limited to one thousand copies, and is obtainable direct from the Optical Society of America, and not through the ordinary trade channels. The book deserves a place among the regular reference treatises on the shelves of all refractionists and other workers interested in the properties of the eye.

T. S.

Optical Measuring Instruments. By L. C. MARTIN, F.R.A.S., D.Sc., A.R.C.S., D.I.C. Pp. x + 270; 172 Figs. (London: Blackie and Son, Ltd., 1924.) Price 17*s*. 6*d*. net.

The author has presented in this work in a concise and convenient form a very thorough survey of optical measuring instruments. The arrangement is particularly serviceable to the student and optical designer as, after a preliminary chapter on general principles, the various types of optical measuring instruments are treated in separate chapters class by class. This method enables the reader to turn at once to the particular chapter dealing with the instrument in which he is at the moment interested and to find there full details of that instrument and also other related instruments so that unnecessary expenditure of time and energy is avoided.

The author first deals with the measurement of length by the measuring microscope and then proceeds to the micrometer microscope and the comparator, the measurement of small differences of length succeeding the absolute measurement of length.

The next chapter is devoted to the divided circle, and its errors; how some of these may be eliminated by suitable means and the remainder have their value determined. The treatment is sufficiently thorough for practically every purpose and is yet sufficiently concise.

Chapters on theodolites, sextants, and levels follow that on the divided circle and the latest developments in these instruments are well explained. From now onward the more specialized types of instruments are taken in succession, chapters being given to rangefinders, spectrometers and autocollimators, spherometers and instruments for measuring curvature, instruments for measuring focal length, photometric instruments, and finally polarimeters and saccharimeters. In a final chapter the subject of errors of observation and the accuracy of measurements are discussed.

The author's method of treatment throughout is very clear and although using mathematics where necessary this is always done in the simplest form suitable to the subject and no reader will lay the book aside as being excessively mathematical; on the contrary it will be widely welcomed as a practical book collecting a large amount of valuable information which up to the present has not been available in a handy form. There is no doubt Dr Martin has expended much time and energy in accumulating the vast store of information now brought together so conveniently.

As a second edition will probably be necessary before very long, it would make the good work still better if the author were to include a chapter on graticules and the errors of quantities measured by their means, especially as such measurements are increasing owing to the rapidity with which they can be made.

P. F. E.

ABSTRACTS OF PATENT SPECIFICATIONS

217280. Lebby, S. L. PROJECTORS.

The lamp has two V or U-shaped filaments, pointing towards the vertex of a lens mirror. The reflector has the upper part of its front surface formed by two spherical curves, struck from two different centres, while its lower half is of dioptric form, with curves struck from three centres. The back silvered surface is spherical.

218547. Pollak, J. E. RANGE-FINDERS.

To ensure that the telescopes at the ends of the base are sighted upon the same object, electrical resistances are arranged in connexion with each so as to give no deflection upon a galvanometer when they are equally inclined to the horizontal. Independent resistances may also be operated to enable the altitude of the object to be obtained.

218548. Pollak, J. E. RANGE-FINDERS.

Electrical resistances are utilized in conjunction with telescopes at the ends of a known base to give a solution of the observational triangle. The result is obtained upon an ohmmeter, graduated to give the range in yards.

218549. Pollak, J. E. RANGE-FINDERS.

In apparatus employing adjustable resistances in connexion with telescopes at the ends of a known base, a preliminary adjustment is made to allow for the effects of resistances which are not measuring resistances.

218716. Courage, D. G. GUNNERY CALCULATORS.

The information required, such as fuse and deflection indication, is determined by the movement of telescopes which give the velocity of the target in azimuth and elevation, and, together with the height-finder, supply the data necessary to read off from a group of curves the necessary settings.

218763. Hilger, A., Ltd., and another. KALEIDOSCOPES.

In a projection kaleidoscope of the type employing a polygonal prism placed between the condenser and the projector lens, means, such as a second similar prism, placed behind the condenser, are provided to illuminate the virtual images of the object to be projected.

218863. Optische Anstalt C. P. Goerz Akt.-Ges. GRINDING LENSES.

The pressure between the lens and the tool is applied by centrifugal force. An annular working surface is formed upon a bowl-shaped member mounted near the edge of a rotating table, and itself rotated by epicyclic gearing. The respective speeds are adjusted until the lens remains stationary in contact with the grinding face, or rolls upon a flange formed upon the top edge of the bowl. The working face may be formed upon the outer surface of the bowl, and the blanks carried upon levers which permit the necessary pressure to be applied by centrifugal action.

218894. Gowlland, E. LIGHT FILTERS.

An anti-glare filter consists of two sheets of glass between which is placed, for instance, a piece of silk fabric, or a number of strips of glass arranged edge-wise, Canada balsam being applied to reduce the diffusion of light.

219112. Duda, F. SPEED-INDICATORS.

The velocity of a projectile, or other quickly-moving body, is determined by photographing it by a camera having several lenses and a common rotating shutter. The interval between the exposures is ascertained by projecting upon the moving sensitive surface a ray of light reflected from one mirror mounted upon a tuning-fork, and also from another which is given a slight shake at the instant of exposure.

219292*. Franklin Optical Co. BI-FOCAL LENSES.

The main lens is made of glass having a relatively low index, and the insert of glass with a higher index, the ratio of power to dispersion being the same for each.

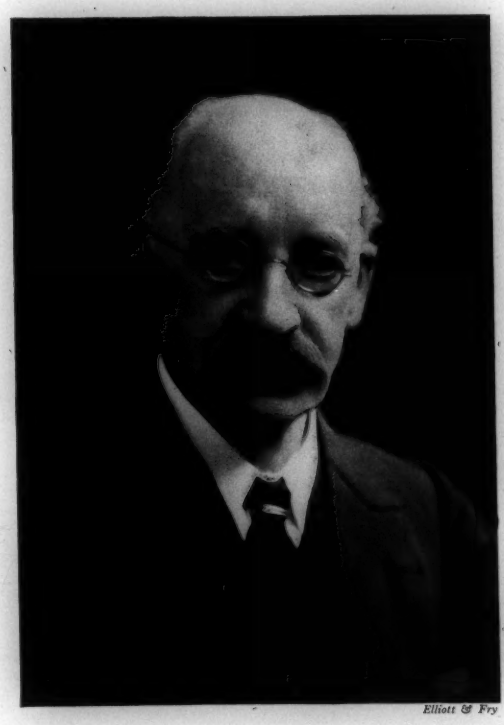
219438. Miethe, A. PROJECTORS.

The reflector of a projection apparatus is protected by a cooling cell, of which the reflecting surface itself may form one wall.

219821. Tallack, H. T. SURVEYING INSTRUMENTS.

The telescope of a surveyors' level is actuated by a snail or wedge, controlled by a micrometer adjustment.

* Specification published before acceptance.



Elliott & Fry

EMERITUS PROFESSOR ARCHIBALD BARR, D.Sc., LL.D., F.R.S.
President of the Optical Society
1923–25